Effects of Polymer-coated Urea on Nitrate Leaching and Nitrogen Uptake by Potato

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Increasing groundwater nitrate concentrations in potato (*Solanum tuberosum* L.) production regions have prompted the need to identify alternative nitrogen management practices. A new type of polymer-coated urea (PCU) called Environmentally Smart Nitrogen (Agrium, Inc., Calgary, AB) is significantly lower in cost than comparable PCUs, but its potential to reduce nitrate leaching and improve fertilizer recovery has not been extensively studied in potato. In 2006 and 2007, four rates of PCU applied at emergence were compared with equivalent rates of soluble N split-applied at emergence and post-hilling. Additional treatments included a 0 N control, two PCU timing treatments (applied at preplant or planting), and a soluble N fertigation simulation. Nitrate leaching, fertilizer N recovery, N use efficiency (NUE), and residual soil inorganic N were measured. Both 2006 and 2007 were low leaching years. Nitrate leaching with PCU (21.3 kg NO_3–N ha^{-1} averaged over N rates) was significantly lower than with split-applied soluble N (26.9 kg NO_3–N ha^{-1}). The soluble N fertigation treatment resulted in similar leaching as PCU at equivalent N rates. Apparent fertilizer N recovery with PCU (65% averaged over four rates) tended to be higher than split-applied soluble N (55%) at equivalent rates (p = 0.059). Residual soil N and NUE were not significantly affected by N source. Under the conditions of this study, PCU significantly reduced leaching and tended to improved N recovery over soluble N applied in two applications and resulted in similar N recovery and nitrate leaching as soluble N applied in six applications.

Intensive irrigated agriculture on coarse-textured soils in the Upper Midwest is contributing to the growing nitrate (NO_3) problem in ground and surface waters (Komor and Anderson, 1993; O'Dell, 2007). Coarse-textured soils have low water-holding capacity and high infiltration rates, making irrigation necessary to produce crops but allowing for the potential movement of soluble pollutants to groundwater. In addition to NO_3–contaminated groundwater, surface waters can also be supplied by shallow aquifers underlying coarse-textured soils, which in turn can affect NO_3 concentrations in the entire watershed. The Upper Mississippi Basin has contributed almost 40% of the total nitrogen flux to the Mississippi River which has been attributed to causing hypoxia in the Gulf of Mexico (Aulenbach et al., 2007). Alternative N management practices are needed to reduce groundwater contamination while maintaining crop yields.

Potato is a high-value crop commonly grown on coarse-textured soils. Production has been expanding in Minnesota since the 1960s, and the state is currently sixth in potato production in the United States (USDA National Agriculture Statistics Service, 2008). Potato requires high N inputs to maximize yields, yet fertilizer N recovery is often low (<50%) due to its shallow root system (Liegel and Walsh, 1976; Bundy and Andraski, 2005). This, coupled with its preference for sandy soils and unpredictable rain events, increases the potential for NO_3 leaching to groundwater under Midwest conditions. Irrigated farming in central Minnesota has been linked to increasing NO_3 concentrations in drinking water since 1969 (Lindholm, 1980). The average well water NO_3–N concentration in the Central Sands region of Minnesota, a popular area for irrigated potato production, was 16.1 mg L^{-1}, well above the drinking water standard of 10 mg L^{-1} (O'Dell, 2007).

Based on research conducted on coarse-textured soils, N applied several times throughout the season resulted in an increase in N utilization by the plant (Errebhi et al., 1998; Vos, 1999). The University of Minnesota currently recommends at least three split applications to reduce leaching on coarse-textured soils (Rosen and Bierman, 2008). Other available fertilizer options include controlled-release fertilizers, which attempt to release N in a way

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Abbreviations: DAP, days after planting; ESN, Environmentally Smart Nitrogen; NUE, nitrogen use efficiency; PCU, polymer-coated urea; SCU, sulfur-coated urea.

that matches plant uptake. Sulfur-coated urea (SCU) resulted in less NO_3 leaching but had mixed results on potato yield and fertilizer N recovery (Waddell et al., 2000). Liegel and Walsh (1976) found that under normal conditions, SCU resulted in reduced yields and lower fertilizer N recovery, although it increased yields and N recovery under severe leaching conditions. Polymer-coated urea tends to have a more predictable release pattern than SCU (Trenkel, 1997; Shaviv, 2000) and has resulted in yields similar to or greater than those with soluble N sources (Shoji et al., 2001; Zvomuya and Rosen, 2001; Hutchinson et al., 2003; Pack et al., 2006). A 2-yr study in Minnesota found that a different PCU (coated with polyolefin) also reduced NO_3 leaching and increased fertilizer N recovery over split applications of urea (Zvomuya et al., 2003).

Even with the reported environmental benefits of PCU fertilizers, economic analyses have shown that PCU was not cost effective for potato producers due to higher prices of coated products (Trenkel, 1997; Zvomuya and Rosen, 2001). Simonne and Hutchinson (2005) concluded that cost-share programs in Florida were needed to offset the cost increase associated with PCU. Recently, however, a new type of PCU was developed by Agrium Inc. that is considerably lower in price. This PCU, called Environmentally Smart Nitrogen (ESN; Agrium Inc., Calgary, AB) has shown promising results in initial studies on potato production (Hopkins et al., 2008; Wilson et al., 2009), but its influence on N uptake characteristics by potato and NO_3 leaching has not been extensively studied. The overall objective of this study was to compare the effects of PCU with soluble N sources on NO_3 leaching, N recovery, and N use efficiency in potato production at varying N rates and timing of application.

Materials and Methods

Field studies were conducted over 2 yr (2006–2007) at the Sand Plain Research Farm in Becker, MN (45°23′ N 93°53′ W). Agronomic aspects of this study were reported previously (Wilson et al., 2009). The soil was an excessively drained Hubbard loamy sand (sandy, mixed, frigid Entic Hapludoll) formed in glacial outwash. The available water-holding capacity in the top 120 cm of soil is 8 cm (USDA–NRCS, 2002). The previous crop in both years was nonirrigated and nonfertilized rye (*Secale cereale* L.).

Representative soil samples from the top 15 cm were taken before planting for routine soil analysis (Brown, 1998). Soil samples from the upper 60 cm were conductimetrically analyzed for KCl extractable nitrate N (NO_3–N) and ammonium N (NH_4–N) (Carlson et al., 1990). Soil pH before planting ranged from 6.6 to 6.8 over the 2 yr, while Bray-P was 31 to 32 mg kg^{-1}, organic matter was 15 to 24 g kg^{-1}, and extractable K was 87 to 108 mg kg^{-1}. Nitrate- and ammonium N in the top 60 cm were 9 and 20 kg ha^{-1} in 2006 and 12 and 17 kg ha^{-1} in 2007, respectively.

The most popular processing potato cultivar in the upper Midwest, 'Russet Burbank', was used for this study. Cut "A" seed on 25 Apr. 2006 and whole "B" seed on 26 Apr. 2007 were hand planted in furrows with 90 cm between rows and approximately 25 cm between seed pieces within the row. Each plot consisted of four 6-m rows, and only the center two rows were sampled or used for harvest. Rows were mechanically hilled at plant emergence. Overhead supplementary irrigation was applied according to the checkbook method to maintain adequate soil moisture (Wright, 2002). Although in 2007, irrigation water was applied more frequently and in excess to ensure that some leaching occurred. A WatchDog Model 2800 weather station (Spectrum Technologies Inc., Plainfield, IL) located in the field sites collected and stored rainfall, air temperature and soil temperature data every 30 min. For further details on crop management methods, refer to Wilson et al. (2009).

Two sources of N, a soluble source and a 90-d release PCU (ESN 44–0–0; Agrium, Inc., Calgary, AB), were compared across several rates and timing schemes, including rates typically used by farmers in Minnesota (Bruening, 1996). The ESN PCU was obtained directly from the manufacturer. Twelve N treatments (Table 1) were replicated five times in a randomized complete block design. The first treatment was a zero N control with triple super phosphate used as the P source at planting. All other treatments received diammonium phosphate as the P source at planting at the same P rate as the zero N control. For Treatments 2 to 5, soluble N was split-applied as urea at emergence–hilling and as 50% granular urea and 50% granular ammonium nitrate at post-hilling on 19 May and 2 June in 2006 and 15 May and 4 June in 2007, respectively. Applications were side-dressed and mechanically incorporated into the hill. Treatment 6 was intended to simulate 28% urea-ammonium nitrate N fertigation: the post-hilling application was further split into five equal applications (approximately 12 d apart), which were applied by hand and watered-in with irrigation. For Treatments 7 to 10, PCU was side-dressed at emergence

Table 1. Nitrogen treatments for 'Russet Burbank' potato.

Treatment	Preplanting	Planting	Emergence and hilling	Post-hilling†	Total
	kg N ha^{-1}				
1‡	0	0	0	0	0
N source: Diammonium phosphate§ at planting + soluble N¶ after planting					
2	0	45	23	1 x 22	90
3	0	45	68	1 x 67	180
4	0	45	113	1 x 112	270
5	0	45	158	1 x 157	360
6	0	45	115	5 x 22	270
N source: Diammonium phosphate§ at planting + polymer-coated urea					
7	0	45	45	0	90
8	0	45	135	0	180
9	0	45	225	0	270
10	0	45	315	0	360
11	225	45	0	0	270
12	0	45 + 225	0	0	270

† Post-hilling N applications were applied all at once or split into five equal applications over time.

‡ Phosphorus in the zero N plot (Treatment 1) was applied as triple super phosphate at the same P rate as diammonium phosphate.

§ 45 kg N ha^{-1} as diammonium phosphate.

¶ Soluble N = urea applied at emergence and urea/ammonium nitrate (1:1) applied at post-hilling.

and incorporated. Preplant PCU (Treatment 11) was broadcast and mechanically incorporated into the soil to a depth of 5 to 10 cm on 14 Apr. 2006 and 18 Apr. 2007 while planting PCU for Treatment 12 was mixed in with starter fertilizer.

Nitrogen supplied by precipitation and irrigation water was also measured. Water samples were collected above the potato canopy and analyzed for NO_3–N and NH_4–N conductimetrically after each event (Carlson et al., 1990). The average total N concentration in irrigation water was 8.6 and 7.1 mg L^{-1} (~95% as NO_3–N) in consecutive years, while total N in rainfall averaged 3.9 mg L^{-1} (~70% as NH_4–N) in both years. Total N supplied by irrigation was 21.3 and 34.7 kg N ha^{-1} in 2006 and 2007, respectively. Total N supplied by rainfall was about 8 kg N ha^{-1} in each year.

For measurement of soil water NO_3 concentration, suction cup samplers with a porous ceramic cup (1 bar high flow; Soil Moisture Equipment, Santa Barbara, CA) were installed 120 cm vertically below the hill in each plot approximately 1 wk after planting according to methods described in Zvomuya et al. (2003). Samplers were installed in three replicates of each treatment. A hand pump was used to apply a suction of 40 kPa to collect soil water draining through the soil at the depth of installation. A depth of 120 cm was assumed to be sufficiently below the root zone and NO_3 in the soil water at this depth is considered to be leachable. Soil water samples were collected approximately once a week or more if drainage was suspected to occur, such as after a rain event of at least 1 cm or more. Sampling began 2 to 3 wk after planting and continued until ground freeze in December. Several samples were also taken after ground thaw during the following spring to determine residual soil water NO_3–N, although these were not used in leaching calculations. Samples were kept frozen until analysis. Nitrate-N and NH_4–N were determined using the diffusion–conductivity method (Carlson et al., 1990).

Daily water percolation at 120 cm below the potato crop was determined with a water balance equation as presented in Waddell et al. (2000). The water balance between two consecutive days was calculated as

$$D = P + I - E - \Delta S \qquad [1]$$

where D is the amount of daily drainage, P is precipitation, I is irrigation water applied, E is evapotranspiration, and ΔS is the change in soil water storage between 2 d. The E values were calculated as a product of the potential evapotranspiration (E_o) estimated by a modified Jensen–Haise equation (Killen, 1984) and the crop coefficient (K_c) at a given crop developmental stage. Initial water storage at the beginning of the season and maximum water storage on any particular day was equal to the soil water holding capacity of the 120-cm soil profile. This method assumes that water percolation did not vary across plots or replicates.

Daily NO_3–N leached was calculated by converting water percolation to a volume basis and multiplying by the NO_3–N concentration of the soil water on that particular day. Since soil water samples were not taken on a daily basis, water NO_3–N concentrations between two consecutive sampling dates were linearly extrapolated for each day to cover the entire sampling period (April–December). Daily fluctuations in NO_3–N concentrations may not be taken into account with linear extrapolation, but possible errors were minimized by sampling at short intervals and by maintaining a continuous vacuum in the suction samplers. Cumulative NO_3–N leached was the sum of all daily leaching events during the sampling period.

Vines were manually harvested from the center two rows of each plot and weighed on 19 September of each year. Approximately 7 d later, tubers were mechanically harvested from the center two rows. Vine and tuber samples from each plot were collected to determine dry matter content and N uptake. Samples were dried at 60°C, weighed for dry matter yield, and then ground with a Wiley mill to pass a 2-mm sieve. Total N in ground samples was determined with a combustion analyzer (model vario EL, Elementar Americas Inc., Mt. Laurel, NJ) following the methods of Horneck and Miller (1998). Nitrogen content of vines and tubers was calculated as the product of dry matter yields and percentage N. Total N content was the sum of vine and tuber N contents.

Apparent fertilizer N recovery was determined by the difference method as explained in Zvomuya et al. (2003):

$$\text{N uptake} = [(N_{\text{FP}} - N_0) / N_{\text{F}}]100 \qquad [2]$$

where N_{FP} is the total N uptake in fertilizer plots, N_0 is the total N uptake in the control plots, and N_{F} is the amount of fertilizer applied. Nitrogen use efficiency was calculated based on a modified method in Zebarth et al. (2004a):

$$\text{NUE} = \frac{\text{DM}_{\text{FP}}}{N_{\text{S}}} \qquad [3]$$

$$N_{\text{S}} = N_0 + N_{\text{F}} \qquad [4]$$

where DM_{FP} is equal to plant dry matter in fertilized plots and N_{S} is crop N supply. Crop N supply (Eq. [4]) was calculated as the sum of plant N accumulation measured at harvest for the 0 N control (N_0) plus fertilizer N applied (N_{F}) (Bittman et al., 2004). The methods to determine N recovery and NUE assume that the uptake of nonfertilizer N from the soil (including N supplied by mineralization, irrigation, and precipitation) is the same for control and fertilizer plots.

After harvest, six soil cores to 60-cm depth were collected from each plot to determine the residual soil inorganic N. Soils were air dried, ground, and extracted with 2 mol L^{-1} KCl. Nitrate-N and NH_4–N in KCl extracts were determined using the diffusion conductivity method (Carlson et al., 1990).

Data from the study were analyzed using PROC MIXED (SAS Institute, 2004) with replicates and years considered as random effects. For leaching data, the analysis was only conducted on cumulative NO_3–N leaching over the growing season. Least square means and contrast statements were used to compare treatment means. Differences among treatments in years (year × treatment interaction), were assessed by year-specific inference using best linear unbiased predictors (BLUPs) as described by Littell et al. (2006). Yield data and N release from the PCU were reported in a companion study (Wilson et al., 2009).

Results and Discussion

Weather

In general, the 2006 and 2007 growing seasons were warmer and drier than the average growing season for the region. The 30-yr average temperature and precipitation from April to September at Becker, MN, were 16.2°C and 55.1 cm, respectively. Temperature averaged 17.1°C and 17.4°C in 2006 and 2007, respectively. In 2006, 52 cm of rainfall (below average by 3.3 cm) was supplemented by 39 cm of irrigation, and in 2007, 45 cm of rainfall (below average by 9.8 cm) was supplemented with 48 cm of irrigation (Fig. 1). Although the crop received less rainfall in 2007, more frequent irrigations increased the total water application to approximately 3 cm above that in 2006.

Nitrate Leaching

Daily NO_3–N leaching patterns varied across years, mainly due to varying weather patterns in 2006 and 2007 (Fig. 2). Total water drainage below 120 cm was 27.5 cm in 2006 versus 56.0 cm in 2007. In 2006, three major rain events (>3 cm) corresponded with three main leaching events at 6, 121, and 130 d after planting (DAP). These occurred very early or very late in the season, however, when soil water NO_3–N concentrations were generally at the lowest (data not presented). There was a significant period where leaching did not occur between 60 and 121 DAP due to dry conditions. During this same

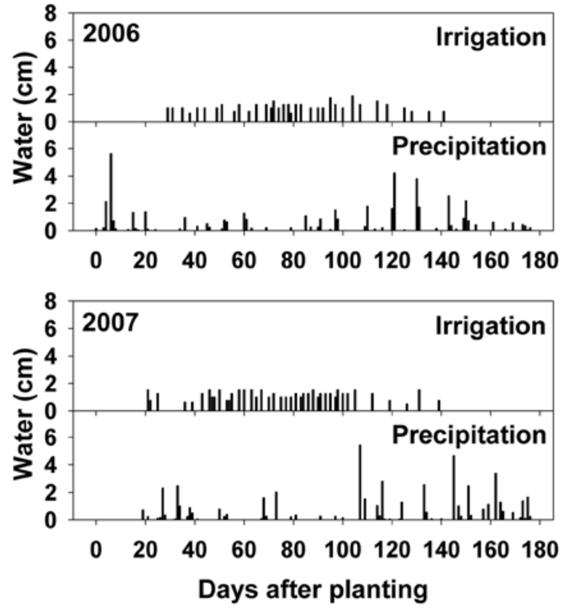

Fig. 1. Distribution of irrigation and precipitation events in 2006 and 2007 at Sand Plains Research Farm, Becker, MN.

interval in 2007, approximately 60% of the leaching occurred even though precipitation between 60 and 121 DAP was only approximately 1 cm greater than in 2006. Irrigation during this time in 2007 exceeded irrigation in 2006 by approximately

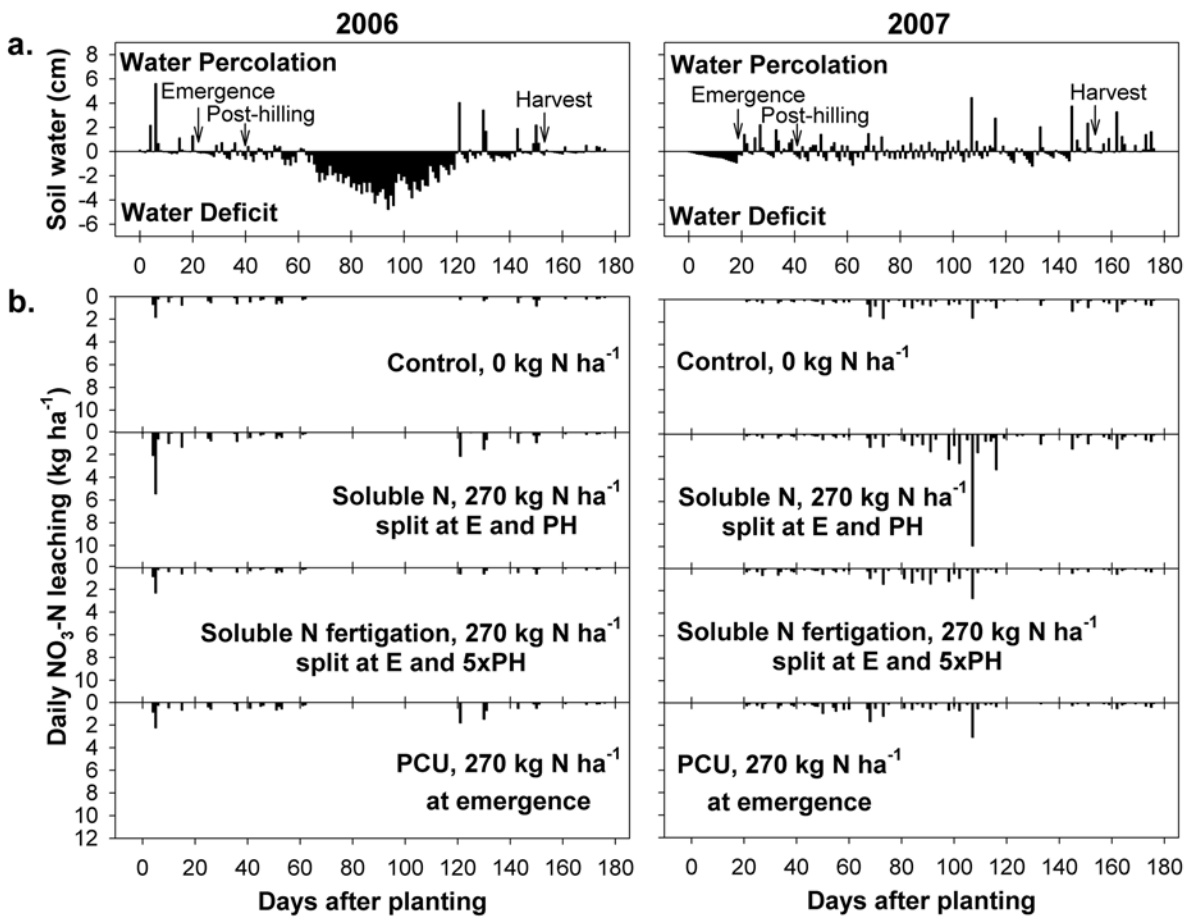

Fig. 2. Soil water balance for the top 120 cm and N source (270 kg N ha^{-1}) effect on daily nitrate leaching in 2006 and 2007. Patterns were similar for each N source at other rates and timing. Soluble N was urea at emergence and urea plus ammonium nitrate for post-hilling applications. E, emergence; PH, post-hilling; PCU, polymer-coated urea.

5 cm. This was intentional and illustrates the influence of more frequent and excessive irrigations on NO_3 leaching.

Three major rain events occurred on 107, 145, and 162 DAP in 2007, but only the event at 107 DAP influenced NO_3–N leaching (>1 kg NO_3–N ha^{-1} leached averaged over treatments). This leaching event occurred the day after an irrigation event, while irrigation had ended for the season by the time rain had occurred on the other dates. In addition, soil water NO_3–N concentrations in 2007 had not reached the low constant concentration stage by 107 DAP (NO_3–N concentration was 8.4 mg L^{-1} averaged over all N treatments), while at 145 and 162 DAP, soil water NO_3–N concentrations were generally at their lowest (1.7 and 2.7 mg NO_3–N L^{-1}, respectively). Other events that greatly influenced leaching took place at 68 and 73 DAP where rainfall (>1.5 cm) followed irrigation events the previous day, and soil water NO_3–N concentrations were relatively high (14.1 and 19.8 mg NO_3–N L^{-1}, respectively). Errebhi et al. (1998) also reported that irrigation followed by rainfall caused significant amounts of leaching.

Cumulative NO_3–N leaching based on the water balance method was significantly affected by N treatment ($p < 0.05$) (Fig. 3); although differences were less than expected on the basis of previous studies (Zvomuya et al., 2003). Most treatments did not cause an increase in NO_3–N leaching compared with the 0 N control. The exceptions were PCU and soluble N at 360 kg N ha^{-1}, two split applications of soluble N at 270 kg N ha^{-1}, and preplant PCU at 270 kg N ha^{-1}. There were no differences between N sources at equivalent rates, except at 270 kg N ha^{-1}. Soluble N and preplant PCU resulted in more NO_3–N leaching than the soluble N fertigation treatment, emergence applied PCU, and PCU applied at planting. When contrasts were used to compare all split-applied soluble N treatments with PCU treatments at equivalent rates (2, 3, 4, and 5 versus 7, 8, 9, and 10), the use of PCU fertilizer significantly reduced NO_3–N leaching compared with soluble N treatments ($p < 0.05$). Nitrate-N leaching averaged over N rates was 23.4 ± 11.6 and 29.3 ± 16.9 kg NO_3–N ha^{-1} for emergence PCU and split soluble N, respectively. There were no significant differences between years, and the year × treatment interaction was not significant (Table 2).

Others have reported NO_3–N leaching for potatoes on sandy soils to range from 71 to 257 kg N ha^{-1} (Hill, 1986; Errebhi et al., 1998; Gasser et al., 2002) with soluble N sources at conventional N rates. In Zvomuya et al. (2003), values for leaching with PCU were reported to range from 7 to 62 kg NO_3–N ha^{-1}, while SCU in Waddell et al. (2000) resulted in 13 to 36 kg NO_3–N ha^{-1} of leaching under sprinkler irrigation. Both studies found that controlled release fertilizers significantly reduced NO_3–N leaching. Under the conditions of this study, NO_3–N leaching with soluble N was typically lower than previously reported values at equivalent N rates, but our results were within the lower ranges for leaching with PCU reported in the literature. This may be due to several reasons, such as the drier-than-average weather conditions, which reduced overall water movement through the soil. Another reason is that several of the previous studies applied N at planting (Hill, 1986; Gasser et al., 2002), whereas the majority of treatments in this study were applied at emergence or later as a current best management practice to reduce NO_3 leaching. Research on potatoes grown on sandy soils suggests that applying the majority of N after emergence reduces NO_3–N leaching (Prunty and Greenland, 1997; Errebhi et al., 1998).

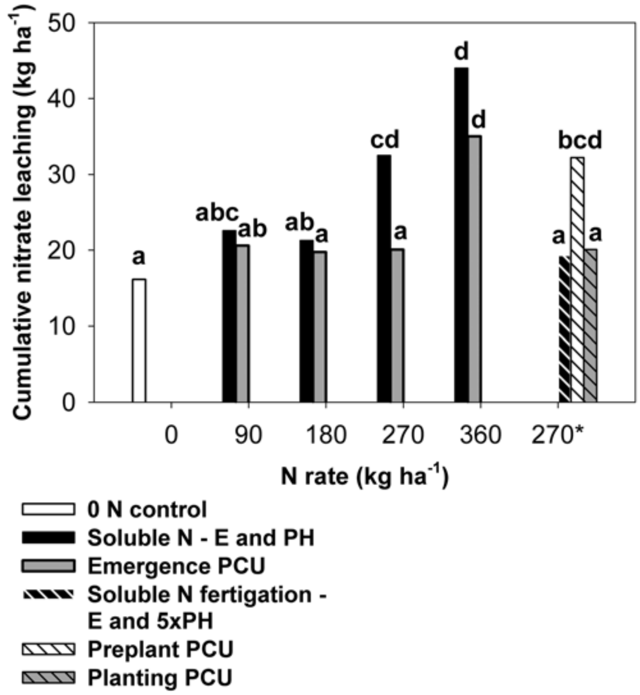

Fig. 3. The effect of N source, rate, and timing on cumulative NO_3–N leached based on the water balance method and averaged over 2006 and 2007. Mean leaching with the same letters are not significantly different ($p > 0.05$). The N timing treatments are represented by *270. E, emergence; PH, post-hilling; PCU, polymer-coated urea.

In the spring following potato harvest, water sampling continued under the succeeding rye crop. Soil water NO_3–N concentrations, averaged across years and N rates, were generally highest in plots that were previously fertilized with N compared with the 0 N control (mean 6.8 ± 3.7 mg L^{-1}). The plots fertilized with split applications of soluble N had an average NO_3–N

Table 2. Results of statistical analyses for N leaching, uptake, recovery, use efficiency, and soil concentration as affected by fertilizer application treatments and years.

Significance	NO_3–N leaching	N uptake			Fertilizer N recovery	N use efficiency	Soil inorganic N		
		Vine	Tuber	Total			Total	NH_4–N	NO_3–N
	kg ha^{-1}					g g^{-1}	mg kg^{-1}		
Year (Y)	NS†	NS	NS	NS	NS	NS	*	*	NS
Treatment (T)	*	*	*	*	NS	*	NS	*	*
Y × T	NS	NS	NS	NS	NS	NS	NS	NS	NS

* Significant at the 0.05 probability level.

† NS, nonsignificant.

concentration of 10.8 ± 5.7 mg L^{-1}, whereas those fertilized with emergence applications of PCU were similar with an average of 10.4 ± 5.9 mg L^{-1}. With N timing treatments (applied at 270 kg N ha^{-1}), spring soil water NO_3–N concentrations varied from 10.1 ± 4.8 mg L^{-1} for the soluble N fertigation treatment and 11.4 ± 3.2 mg L^{-1} for preplant applied PCU to 12.6 ± 7.7 mg L^{-1} for planting applied PCU. Zvomuya et al. (2003) reported that plots fertilized with PCU had higher soil water NO_3–N concentrations the following spring compared with those fertilized with urea or the 0 N control. The PCU used in the current research, however, had a faster N release rate (Wilson et al., 2009), and soil water NO_3–N concentrations were similar between previously fertilized plots, regardless of N source. The mean soil water NO_3–N concentrations in N fertilized plots were above the 10 mg L^{-1} limit, indicating the importance of a subsequent cover crop to reduce NO_3 concentrations and potential leaching.

Nitrogen Uptake, Fertilizer Nitrogen Recovery, and Nitrogen Use Efficiency

The year did not affect N uptake, apparent fertilizer N recovery, or N use efficiency, nor were there significant interactions between main effects (Table 2). Nitrogen content of vines and tubers was significantly affected by N treatment ($p < 0.05$) (Table 3). Averaged over years, all treatments with fertilizer applications greater than 90 kg N ha^{-1} increased vine N content over the 0 N control, and vine N uptake linearly increased as N rate increased for both N sources. Nitrogen timing treatments did not affect vine N content, except for PCU at planting, which resulted in higher vine N content than that for preplant or emergence PCU. The addition of N significantly increased tuber N content over the control treatment, but N rate did not significantly increase tuber N uptake above 180 kg N ha^{-1}. At the 270 kg N ha^{-1} rate, tuber N content with PCU was not affected by timing of application.

As expected, total N content was significantly higher with addition of N fertilizers than with the control (Table 3). For both emergence PCU and split soluble N, total N uptake increased linearly with increasing N rate. With PCU timing treatments, planting PCU resulted in significantly higher total N compared with the preplant PCU treatment. Based on contrast statements, emergence applied PCU resulted in significantly more plant N accumulation (237.6 kg N ha^{-1}) than two split applications of soluble N (213.9 kg N ha^{-1}).

Apparent fertilizer N recovery ranged from 45 to 76% and declined linearly as N rate increased for both N sources (Table 3). Within each N rate, N source did not significantly affect N recovery. However, N recovery tended to be higher ($p = 0.059$) with emergence-applied PCU (65%) compared with two split applications of soluble N (55%) when averaged over N rate. Zvomuya et al. (2003) also concluded that the application of PCU increased recovery of fertilizer applied N over that with soluble N applications, whereas Pack et al. (2006) found that only some

Table 3. Nitrogen content, fertilizer recovery and nitrogen use efficiency for 'Russet Burbank' potato as affected by N source, rate, and timing combined over years. Nitrogen sources include soluble N and polymer-coated urea (PCU).

Treatment no.	N source	N rate†	Timing: PP, P, E, PH‡	Nitrogen content: Vine§	Nitrogen content: Tuber	Nitrogen content: Total¶	Fertilizer N recovery	N use efficiency
				kg ha^{-1}			%	g g^{-1}
1	None	0	0, 0, 0, 0	8.6 e	92.2 f	100.8 f	–	120.5 a
2	Soluble N#	90	0, 45, 23, 22	14.6 de	137.0 e	150.3 e	66.6 a	86.0 b
3	Soluble N	180	0, 45, 68, 67	26.3 cd	176.8 cd	203.1 d	57.0 a	65.9 c
4	Soluble N	270	0, 45, 113, 112	38.7 bc	201.2 abc	239.9 bc	51.7 a	52.7 d
5	Soluble N	360	0, 45, 158, 157	64.6 a	197.6 abc	262.2 ab	45.0 a	40.3 ef
6	Soluble N	270	0, 45, 115, 5×22	46.7 b	194.3 abc	240.9 bc	52.1 a	50.4 de
7	PCU	90	0, 45, 45, 0	16.7 de	152.9 de	169.5 e	76.6 a	88.2 b
8	PCU	180	0, 45, 135, 0	30.8 c	197.3 abc	228.1 cd	71.0 a	70.2 c
9	PCU	270	0, 45, 225, 0	48.7 b	213.5 ab	262.1 ab	60.0 a	52.8 d
10	PCU	360	0, 45, 315, 0	71.3 a	219.1 a	290.4 a	52.9 a	39.8 f
11	PCU	270	225, 45, 0, 0	47.1 b	187.4 bc	234.5 bc	49.7 a	49.9 def
12	PCU	270	0, 270, 0, 0	72.7 a	210.0 ab	282.6 a	67.6 a	50.3 de
	Contrasts††							
2 splits soluble N vs. Emergence PCU (2, 3, 4, 5 vs. 7, 8, 9, 10)				††	*	*	††	NS‡‡
Linear Response to Soluble N (Treatments 2, 3, 4, 5)				*	*	*	*	*
Quadratic Response to Soluble N (Treatments 2, 3, 4, 5)				NS	*	NS	NS	NS
Linear response to PCU (Treatments 7, 8, 9, 10)				*	*	*	*	*
Quadratic response to PCU (Treatments 7, 8, 9, 10)				NS	*	NS	NS	NS

* Significant at the 0.05 probability level.

† N rate is in kg N ha^{-1}; 45 kg ha^{-1} of nitrogen at planting is from diammonium phosphate.

‡ PP, preplanting; P, planting; E, emergence and hilling; PH, post-hilling.

§ Means followed by the same letter in columns are not significantly different ($p > 0.05$).

¶ Total N = vine + tuber N content.

Soluble N = urea applied at emergence and urea/ammonium nitrate (1:1) applied at post-hilling.

†† Significant at the 0.10 probability level.

‡‡ NS, nonsignificant.

controlled-release fertilizers improved N recovery. Low N recovery with certain PCUs in the latter study was attributed to "lockout," where coated prills never released the fertilizer or improper release rates for potatoes were used (Pack et al., 2006). This illustrates the importance of evaluating new PCU products from both an agronomic and an environmental standpoint.

Another important measure of potato N utilization is NUE. The addition of N significantly reduced NUE over the 0 N control (Table 3). An increase in N rate significantly reduced NUE linearly for both N sources. Emergence PCU tended to result in numerically higher NUE than soluble N at the lower N rates, but overall differences between N sources were not significant. All N timing and source treatments at 270 kg N ha^{-1} also resulted in similar NUE. Zebarth et al. (2004a) reported comparable NUE under dry conditions for potatoes fertilized with soluble N at hilling (40–92%)

Nitrogen content values and N recovery results presented in this study are consistent with other studies conducted under low leaching conditions (Errebhi et al., 1998; Zebarth et al., 2004b). In contrast, others reported lower values under varying conditions. Zvomuya et al. (2003) argued that low N recovery in 2 out of 3 yr was due to higher immobilization of applied N caused by the previous winter rye crop, which had a high C-to-N ratio. In the third year, which had similar N recovery values to the current study, potatoes followed soybean [*Glycine max* (L.) Merr.]. Potatoes in the present study followed winter rye in both years, and recovery values were relatively high, suggesting other factors may have differed between the two studies. Pack et al. (2006) used N rates of 146 and 225 kg N ha^{-1} on Atlantic potatoes and found comparable vine N contents (41–99 kg N ha^{-1}) to Russet Burbank in the present study, but tuber N uptake (76–122 kg N ha^{-1}) and N recovery (18–47%) reported by Pack et al. (2006) were much lower. The authors indicated that conditions were drier than normal, but large precipitation events occurred early in the season. Bundy and Andraski (2005) also found low N recovery (<50%) for potatoes fertilized with 224 kg N ha^{-1} under above-normal precipitation conditions.

Table 4. Post-harvest soil inorganic N (0–60 cm) as affected by year.

Year	Soil inorganic N		
	Total†	NH_4–N	NO_3–N
	mg kg^{-1}		
2006	9.5 a‡	7.1 a	2.5 a
2007	5.0 b	2.4 b	2.5 a

† Total = NH_4–N + NO_3–N.

‡ Means followed by the same letter in columns are not significantly different.

Residual Soil Nitrate

The year × treatment interaction was not significant for total residual soil inorganic N, NH_4–N, or NO_3–N (Table 2). Residual total inorganic soil N and NH_4–N in the top 60 cm were greater in 2006 than in 2007 (Table 4). Residual soil NO_3–N was not affected by year. The difference between years with soil NH_4–N (hence total N) but not NO_3–N is unclear. Leaching events occurred within 1 wk before soil sampling dates in both years and may have moved soil NO_3–N below the sampling depth without affecting soil NH_4–N concentrations.

Nitrogen treatments did not significantly affect total soil inorganic N concentrations in the top 60 cm, but soil NO_3–N and NH_4–N did differ among treatments (Table 5). Overall, only application of PCU at planting and the soluble N fertigation treatment significantly increased residual soil NH_4–N over the zero N control. For soil NO_3–N, the highest N rate (360 kg N ha^{-1}) for both N sources (Treatments 5 and 10), as well as the soluble N fertigation treatment, preplant PCU, and planting PCU (Treatments 6, 11, and 12, respectively), resulted in significantly higher levels than the control. For all residual soil inorganic N components, there was no difference based on contrasts between N sources when applied at equivalent rates ($p > 0.10$). In addition,

Table 5. Post-harvest soil inorganic N (0–60 cm) as affected by N source, rate, and timing combined over years. Nitrogen sources include soluble N and polymer-coated urea (PCU).

Treatment no.	N source	N rate†	Timing	Soil inorganic N		
			PP, P, E, PH‡	Total§	NH_4–N	NO_3–N
				mg kg^{-1}		
1	None	0	0, 0, 0, 0	6.0 a¶	4.2 c	1.8 c
2	Soluble N#	90	0, 45, 23, 22	6.4 a	4.3 c	2.1 bc
3	Soluble N	180	0, 45, 68, 67	6.9 a	4.8 bc	2.2 bc
4	Soluble N	270	0, 45, 113, 112	6.5 a	4.2 c	2.3 bc
5	Soluble N	360	0, 45, 158, 157	7.3 a	4.6 bc	2.7 ab
6	Soluble N	270	0, 45, 115, 5×22	9.0 a	6.2 a	2.8 ab
7	PCU	90	0, 45, 45, 0	7.1 a	4.8 bc	2.3 bc
8	PCU	180	0, 45, 135, 0	7.1 a	4.8 bc	2.3 bc
9	PCU	270	0, 45, 225, 0	7.2 a	4.7 bc	2.5 abc
10	PCU	360	0, 45, 315, 0	7.5 a	4.3 c	3.1 a
11	PCU	270	225, 45, 0, 0	7.3 a	4.7 bc	2.6 ab
12	PCU	270	0, 270, 0, 0	8.7 a	5.6 ab	3.1 a

† N rate is in kg N ha^{-1}; 45 kg ha^{-1} of nitrogen at planting is from diammonium phosphate.

‡ PP, preplanting; P, planting; E, emergence and hilling; PH, post-hilling.

§ Total N = vine + tuber N content.

¶ Means followed by the same letter in columns are not significantly different ($p > 0.05$).

Soluble N = urea applied at emergence and urea/ammonium nitrate (1:1) applied at post-hilling.

linear and quadratic trends for NO_3–N, NH_4–N, and total N were not significant. Zvomuya et al. (2003) concluded that a cover crop following the use of PCU fertilizer was needed to scavenge high amounts of residual soil N because in that study PCU only released approximately 60% of N by the time of harvest. With the PCU formulation tested in the present study, residual soil N did not differ between fertilizer sources and over 90% of the N had been released by harvest (Wilson et al., 2009). However, since NO_3 was still present in the post-harvest soil solution, a cover crop is still recommended to minimize NO_3 losses.

Conclusions

Under the conditions of this study, our results show that ESN, a new economical type of PCU, can significantly reduce NO_3 leaching and improve apparent N recovery over two split applications of soluble N at equivalent N rates. Others have found similar results with different PCUs, but residual soil N after harvest was higher after the use of PCU, indicating that significant losses could occur in the fall as NO_3–N leaching. Our data suggest that the new formulation of PCU does not significantly increase post-harvest soil N over conventional practices for potato. The soluble N fertigation treatment also significantly reduced NO_3 leaching over two split applications of soluble N (at equivalent rates), but it did not improve N recovery and significantly increased residual soil NO_3–N and NH_4–N. While proper N management is important to reduce NO_3 leaching, irrigation timing plays an important role as well. Nitrate leaching was more pronounced when irrigation and precipitation events closely followed each other. If a large water drainage event occurred during peak soil water NO_3–N concentrations, the loss of N could be significant. While it is difficult to manage irrigation in climates with unpredictable rainfall, the use of PCU fertilizers may help to minimize NO_3 losses under conditions conducive to leaching.

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Groundwater nitrate contamination costs: A survey of private well owners

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Abstract: Groundwater is an important source of drinking water in Minnesota and nationwide. In Minnesota, 5% to 10% of drinking water wells have nitrate (NO_3) concentrations that exceed health standards. Well owners incur direct costs associated with the presence of NO_3, including costs related to treatment systems, well replacement, and purchasing of bottled water. The objective of this study was to quantify actual amounts spent by private well owners when NO_3 levels are elevated, regardless of whether the owners are aware of the contamination. Survey questionnaires asking about well characteristics, NO_3 testing, and costs of actions taken in response to elevated NO_3 were mailed to 800 private well owners in the central sand plains of Minnesota. Sixty percent of recipients returned surveys and then were sent water sampling bottles, of which 77% were returned. Nitrate was determined in the returned water samples. About 6% of wells tested greater than the US Environmental Protection Agency health standard maximum of 10 mg L^{-1} (10 ppm) nitrate-nitrogen. Less than one-third of respondents had tested their water for NO_3 within the past three years. Average remediation costs were \$190 y^{-1} to buy bottled water, \$800 to buy a NO_3 removal system plus \$100 y^{-1} for maintenance, and \$7,200 to install a new well. Of well owners with nitrate-nitrogen over 10 mg L^{-1}, 24% bought bottled water, 21% installed treatment systems, 24% installed new wells, and 31% were unaware of the contamination and took no actions. Water resource planners can compare the costs described in this study to the costs of preventing aquifer contamination through education and technical and financial support. This study also demonstrates a method for representative sampling of private wells without on-site visits, and the continued need for educational programs related to routine testing.

Key words: bottled water—drinking water—groundwater quality—nitrate test kit—sand plains—sandy outwash

About 70% of Minnesotans get their drinking water from groundwater, including more than one million people (23%) who rely on private wells. Nationwide, 44 million Americans—15% of the population—get their water from private drinking water wells (Hutson et al. 2004).

Elevated nitrate (NO_3) concentrations in drinking water can cause methemoglobinemia (blue baby syndrome) in infants. In addition, some research has suggested that long-term consumption of NO_3 is associated with certain cancers, but evidence is unclear (Fewtrell 2004; Rademacher et al. 1992). The US Environmental Protection Agency set a maximum contaminant level for nitrate-nitrogen (NO_3-N) of 10 mg L^{-1} (or 10 ppm) as a safe concentration for infants (US Environmental Protection Agency 2002).

In Minnesota, natural background concentrations of NO_3-N in groundwater are less than 1 mg L^{-1} (Minnesota Pollution Control Agency [MPCA] 2001). Sources of NO_3 contamination include fertilizer, animal manure, human waste (sewage or septage), and atmospheric deposition (e.g., nitrous oxides from combustion). Contamination is more likely in areas of deep sandy glacial outwash deposits, sometimes found over loamy glacial till or lake sediments, such as those in central Minnesota. Wells in these vulnerable areas often draw drinking water from surficial aquifers, i.e., aquifers above bedrock with no clay or rock confining layer protecting them from contaminants in surface recharge water. Sand point wells are common in these areas. Sand points, also known as driven-point, well points, or slam wells, are constructed by driving a pipe into relatively loose soils. They are generally less than 7-m (25-ft) deep because of pumping limits. Sand points can be susceptible to contamination because of their lack of grouting, shallowness, and lack of a confining layer.

An estimated 7% of all public and private wells in Minnesota exceed the maximum contaminant level for NO_3-N (MPCA 2006). This estimate is based on several databases that are biased toward newer wells that probably have lower NO_3 concentrations. An MPCA study of vulnerable aquifers measured >10 mg L^{-1} NO_3-N in 3.3% of wells sampled; however, this was a study of aquifers (not wells), so only deep wells in nonagricultural areas were sampled and the upper parts of aquifers were not represented (MPCA 1998). Higher contamination rates would be expected in agricultural areas and surficial aquifers. Of the samples brought to voluntary well water testing clinics sponsored by the Minnesota Department of Agriculture, nearly 8% were over 10 mg L^{-1} NO_3-N (Minnesota Department of Agriculture 2006). The clinics are targeted to areas most vulnerable to NO_3 contamination, and participation may be biased towards people who suspect they are at increased risk for NO_3 contamination.

Some areas of Minnesota have much higher-than-average rates of contamination, but statewide NO_3-N concentrations reported in Minnesota wells are lower than those of neighboring states. In Iowa, representative sampling of rural wells from 1988 to 1991 measured 18% to 20% of wells over 10 mg L^{-1} (Libra et al. 1993). A recent Wisconsin aggregation of several water quality databases found that 12% of wells statewide exceeded 10 mg L^{-1} NO_3-N, and rates in a few counties exceeded 20% (Wisconsin Groundwater Coordinating Council 2006).

Costs of preventing groundwater contamination commonly relate to providing education, technical support, and financial incentives to encourage desired practices. Water resource researchers and planners (including state, county, and city officials, and private consultants) need an understand-

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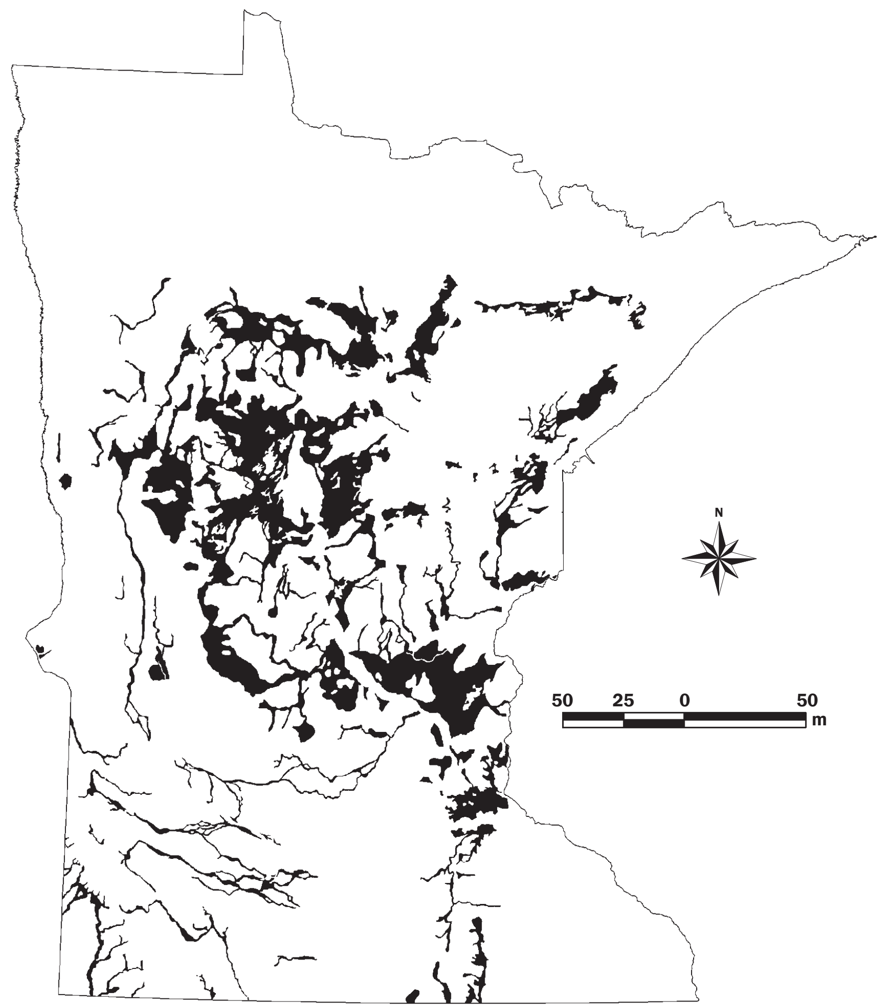
ing of the costs of NO3 contamination to be able to justify and allocate the costs of groundwater protection. Once an aquifer is contaminated, every well owner tapped into that aquifer may bear costs of treating the water or finding another source. These costs have not been well analyzed. Most studies reviewed by Phillips et al. (1999) used the contingent valuation method which asks people to assess their willingness to pay for drinking water quality. Other studies estimated the effect of erosion on surface water treatment, morbidity and mortality costs, or costs of avoiding groundwater pollution. None of the studies summarized the actual amount spent to remediate contaminated well water. Pottebaum (1990) gathered information about costs of treatment systems but did not examine the rate at which well owners would install systems.

The primary purpose of this study was to determine how private well owners in the glacial outwash soils of Minnesota respond to elevated NO_3 concentrations and to quantify their costs. Other objectives were to demonstrate a low-cost statistical sampling method for determining NO_3 concentrations in private wells and to examine well owners' perceptions and attitudes about drinking water quality to help water resource planners and researchers address NO_3 problems more effectively.

Figure 1
Sandy outwash regions of Minnesota.



Note: Areas with the attribute "Outwash—Undivided as to Moraine Association" from Hobbs and Goebel (1982).

Materials and Methods

The study focused on areas of deep sandy glacial deposits in central Minnesota (figure 1). Land cover across the region is about 20% lakes and wetlands, about 40% agricultural, and about 40% forest and brush, with small amounts of developed land including communities and recreational properties. Almost 10% of the cropland in the region is irrigated.

A mail survey was developed and targeted at owners of private wells in 11 counties with high proportions of sandy glacial outwash: Becker, Cass, Dakota, Hubbard, Itasca, Morrison, Otter Tail, Sherburne, Stearns, Todd, and Wadena (figure 2). To avoid homeowners on municipal water systems and to target sandy outwash areas, the mailing addresses were identified by starting with land parcel databases from each county. Parcels were identified by township or municipality, so those within municipal boundaries could be easily eliminated. Parcels were also eliminated if they had no buildings, were public properties, had out-of-state addresses or incomplete addresses, or had the same owner as a previous parcel. The list was then limited to properties on sandy outwash deposits by using a geographic information system (GIS) overlay of surficial geology—specifically, areas labeled "Outwash—Undivided as to Moraine Association" from the Minnesota Geological Survey map of quaternary (surficial) geology acquired from the Land Management Information Center (figure 1; Hobbs and Goebel 1982). If the list of parcels for a county was not in a GIS format, the list was limited to properties in townships primarily on sandy outwash. The resulting list of parcels was divided into homesteaded (owner address same as property address) and nonhomesteaded properties. Nonhomesteaded properties were thought to be second homes and recreational properties. From the final list, 600 addresses were randomly selected from the homesteaded parcels and 200 addresses from the nonhomesteaded parcels.

An alternative source of well owner addresses was the Minnesota County Well Index (CWI), a database which includes the location, initial NO_3 concentration, depth, and geology of wells across the state. We chose not to draw the sample from the CWI because it contains only a fraction of the wells in the state, including very few wells drilled before 1974, and it probably under-represents sand point wells (Minnesota Geological Survey and Minnesota Department of Health 2007; Wahl and Tipping 1991).

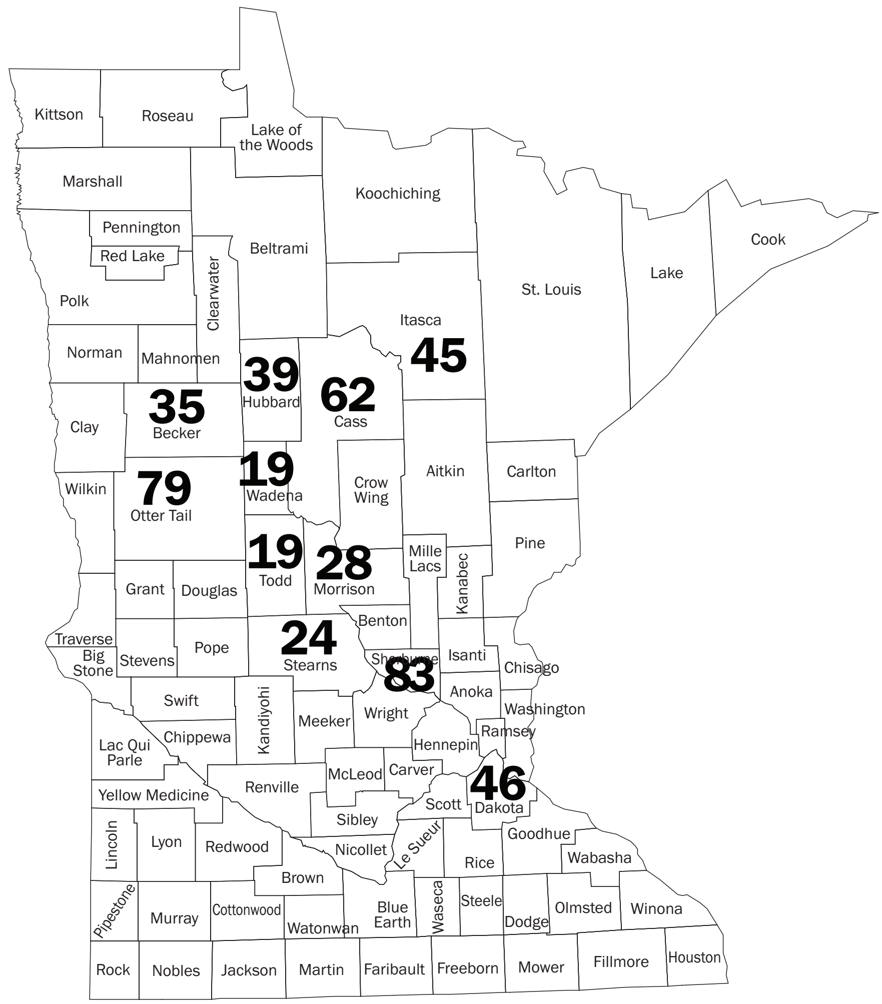


Figure 2
Distribution of returned surveys.

The survey methodology followed procedures described by Dillman (2000). In the summer of 2006, the 800 property owners were sent a survey with 25 questions about characteristics of their well, NO_3 testing of the well, actions taken in response to elevated NO_3 concentrations, costs of these actions, and respondents' concerns and perceptions about water quality. The cover letter offered participants a free NO_3 testing kit to encourage participation and as a low-cost method to collect NO_3 measurements for each well. A week later, a reminder postcard was sent to all addresses. Three weeks after the initial mailing, a duplicate survey was sent to nonrespondents. After three months, 483 people (60%) had returned surveys. Response rates were the same for homesteaded and nonhomesteaded properties. Respondents were sent a NO_3 testing kit consisting of instructions, a 120-mL (4-oz) bottle, and return postage. Water samples were returned by 370 (77%) of the people who were sent kits. If respondents indicated they had a NO_3 treatment system, they were sent two bottles and asked to sample both before and after the treatment system. Participants were asked to take the sample immediately before mailing it and to mail it early in the week. Samples were analyzed within a day of arriving at the lab. Levels of NO_3-N in the water samples were determined using a Hach DR4000 or DR5000 spectrophotometer (method 10049, Hach 2005). Before analysis, 1 ml (0.03 oz) of 1% HCl solution was added to a sample of about 100 ml (3.4 oz). If results were over 10 mg L^{-1}, a 10× dilution of the sample was analyzed.

Survey results were used to estimate average actual expenditures for treating or replacing contaminated water. The actions of well owners who were aware of the NO_3-N concentration of their well were compared to those who were not aware by using chi-squared tests. Although respondents were allowed to report duplicate responses (e.g., they may both drink bottled water and have a treatment system), duplicate answers were removed for the chi-squared analysis by assigning each respondent to a single action in the priority order of new well installation, treatment system, and then drinking bottled water. A logistic regression was used to model the occurrence of elevated NO_3 concentrations from well type, well age, and surrounding land use. Pearson's chi-squared tests were used to determine differences in responses between people who are concerned versus not concerned about NO_3 contamination and differences among types of water quality concerns. Data analysis was done with R statistical software (R Development Core Team 2006).

Results and Discussion

Table 1 and figure 3 are based on results from three survey questions asking about well age, depth, and type of construction. Most respondents (77%) knew all three characteristics. About two-thirds of the wells were drilled, and one-fifth were sand point wells. The proportion of sand points was even lower among the newer wells. At least one-third of the wells can be considered susceptible to contamination because they were a sand point, more than 30 years old, or less than 50 ft (15 m) deep. At least 40% of the wells can be considered less susceptible because they were drilled and they were either less than 15 years old or greater than 100 ft (30 m) deep.

The age categories of 30 and 15 years were chosen to roughly correspond to the implementation of Minnesota's Water Well Construction Code in 1974 and the Minnesota Ground Water Protection Act of 1989. The 1974 code required well drillers to submit logs for every well installed. The 1989 Act improved compliance with well construction and reporting standards (Helland 2001). Data from most well logs since 1974 have been entered into Minnesota's CWI. The code also applies to homeowners installing sand point wells, but the compliance rate is unknown. At least 15% of the drinking water wells in this survey are not included in the CWI because they were installed before

Table 1
Reported well characteristics.

Depth	Age <15 y	15 to 30 yr	>30 yr	Don't know	Sum
All well types (*N* = 468)					
<50 ft	5%	8%	7%	2%	22%
51 to 100 ft	20%	14%	3%	1%	37%
101 to 300 ft	12%	9%	2%	0%	23%
>300 ft	1%	1%	0%	0%	2%
Don't know	5%	5%	3%	3%	16%
Sum	43%	37%	15%	6%	100%
Drilled wells (*N* = 304)					
<50 ft	1%	1%	1%	0%	3%
51 to 100 ft	19%	12%	1%	1%	33%
101 to 300 ft	11%	8%	2%	0%	21%
>300 ft	1%	1%	0%	0%	2%
Don't know	2%	2%	0%	1%	6%
Sum	34%	25%	4%	2%	65%
Driven or sand point wells (*N* = 104)					
<50 ft	3%	7%	6%	1%	17%
51 to 300 ft*	0%	1%	1%	0%	3%
Don't know	0%	1%	1%	0%	2%
Sum	4%	9%	8%	2%	22%

Note: English units are used to match the way questions were asked in our survey questionnaire.
* Sand point wells are generally no deeper than 25 feet.

mid-1970. When asked if their well had a CWI number, 22% of respondents said yes, 29% said no, and 50% did not know. Among owners of sand point wells, none said yes, 57% said no, and 43% did not know.

Three-quarters of the tested wells had NO_3-N concentrations below 1 mg L^{-1} (figure 4). Almost 6% tested greater than 10 mg L^{-1}. This rate is comparable with results from other studies in Minnesota discussed in the introduction. Surprisingly, NO_3 concentrations did not differ among the well types, but the odds of elevated NO_3 concentrations were significantly higher in wells where the principal land use within one-quarter mile was agricultural (table 2).

The Minnesota Department of Health recommends a routine NO_3 test every two to three years for private wells used for drinking water (Minnesota Department of Health 2007). Only 29% of respondents had tested their well water for NO_3 within the past three years (figure 5). Of the remainder who had not tested in the past three years, nearly three-quarters did not feel a need to test because either they did not drink the water, the water was filtered, or they presumed the water was fine (table 3). Some were not aware that their carbon filters and water softeners did not remove NO_3. Cost and inconvenience were less common barriers to testing.

Responses to and Costs of Elevated Nitrate. Responses to elevated nitrate vary partly because some well owners do not know their water NO_3 concentration and others choose to respond at various concentrations. In this survey, half of respondents said they would begin treating or finding an alternative water source before the concentration reached 10 mg L^{-1} NO_3-N, while the other half would wait until it reached 10 or higher (figure 6). When they decide to take action, 74% said they would get (or already have) a NO_3 removal system (table 4, column 1). (Respondents were told the approximate cost of a system when answering this question.) However, actual actions differ from intended actions: treatment systems were installed by only 28% of all respondents who thought they had water with more than 10 mg L^{-1} NO_3-N (table 5, column 7).

Reported costs of responses to elevated NO_3 are shown in table 6. Average expenses in response to NO_3 contamination were \$190 y^{-1} to buy bottled water, \$800 to buy a NO_3 removal system plus \$100 y^{-1} for maintenance, and \$7,200 to install a new well. To avoid NO_3 contamination, a new well may be drilled into a deep aquifer. These deeper waters typically have a high mineral content requiring the additional cost of a water softener. Reported annual maintenance costs for a treatment system may be limited to filter replacement and may not include the cost of electricity or the cost of waste water disposal. Reverse osmosis systems typically generate at least four units of waste water for each unit of product water.

Total direct spending for elevated NO_3 concentrations was calculated by summing the costs of each response to NO_3 contamination after weighting the costs by the proportion of well owners choosing each response. To estimate the level of behaviors attributable to NO_3 contamination rather than to other concerns, the prevalence of behaviors among well owners with less than 2 mg L^{-1} NO_3-N was subtracted from the prevalence among well owners with greater than 10 mg L^{-1} NO_3-N (table 4, column 5). This was multiplied by the average cost of each response from table 6. Thus, where NO_3 concentrations are elevated, an additional 16% of the population bought treatment systems at an average cost of \$798 plus \$100 y^{-1}, 16% bought bottled water at a cost of \$190 y^{-1}, 25% installed a new well at a cost of \$7,200, and the remainder continued their same behavior at no additional cost. The result of summing these weighted costs is \$1,927 in initial costs plus \$46 y^{-1}. This represents the average one-time cost per well if the NO_3-N concentration in an aquifer rose above 10 mg L^{-1}. If the cost of a new well were spread over 50 years and the cost of the treatment system were spread over 20 years, then the average long-term annual cost per well of elevated NO_3 concentrations is \$89. The largest component of the one-time cost is attributed to the 25% of people who installed a new well. That proportion is based on the eight people in this survey who said they installed a new well because of elevated NO_3 concentrations.

Spending for NO_3 contamination would likely be higher if all well owners were aware of contamination. In fact, most well owners have not tested their water recently. Once they learn about contamination, they may drink bottled water or do nothing for some time before buying a treatment system or replacing a well. Thus, rates of installing treatment systems or taking other actions would be higher if every well owner was aware of nitrate concentrations and had time to respond. Table 5 illustrates the higher rates of actions taken by people who knew the results from a recent well water test.

An alternative method for calculating costs is based on incremental NO_3 concentrations: the cost of using a NO_3 removal system to reduce a NO_3-N concentration by 1 mg L^{-1} was calculated by dividing the cost of each individual NO_3 removal system by the reduction in NO_3-N achieved by that system (data not shown). By this calculation, the average cost to reduce NO_3-N by 1 mg L^{-1} was \$227 in initial costs plus \$13 y^{-1} for all systems that were treating NO_3-contaminated water.

This study assumes that costs of NO_3 contamination can be separated from other costs. In reality, well owners likely make decisions about treating or replacing their drinking water source based on multiple factors including perceptions of various contaminants, taste, convenience, cost, and reliability. The survey did not attempt to assess the relative importance of these other factors in drinking water choices.

The survey was designed to estimate replacement costs represented by either treating contaminated water or finding an alternative source. Replacement costs do not represent the total societal costs of NO_3 contamination but help trace economic flows and thus are useful for planning at a local level. Total costs of NO_3 contamination are better represented by the willingness of individuals to pay for risk reduction (Kuchler and Golan 1999), which was not addressed by this survey.

Perceptions and Attitudes. Few respondents perceived a decline in groundwater quality, and 62% felt they had ample opportunities to learn about their water quality (figure 7). Concern about NO_3 contamination was about the same as concern about bacterial or chemical contamination but was significantly greater than concern about contamination with iron or other minerals (figure 8). Compared with people who are not concerned, the 71% of people who are "very" or "somewhat" concerned about NO_3 contamination were significantly more likely to say they test their water, drink bottled water, and think property values have declined in the county due to poor water quality (data not shown). The perception of

Figure 3
Reported well characteristics.

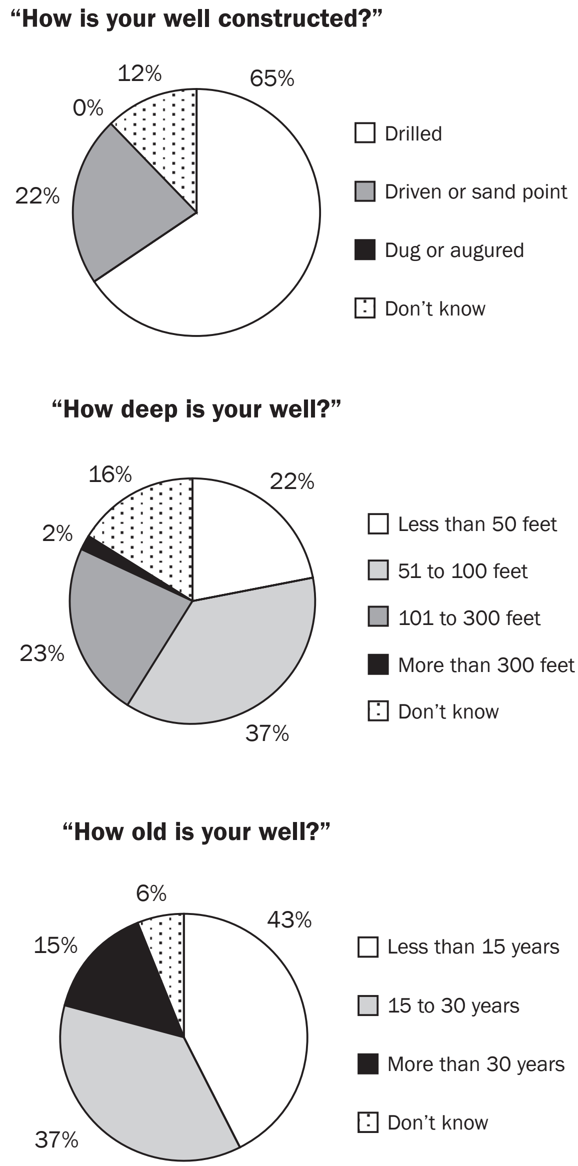


Figure 4
Well water nitrate-nitrogen concentrations of 370 water samples submitted for testing.

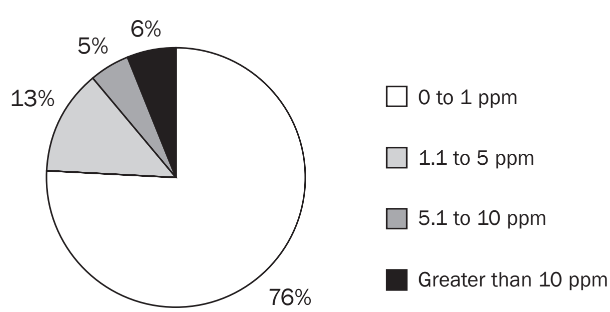


Table 2
Where are nitrate-nitrogen concentrations elevated?

Category of wells	Proportion of the category of wells with the following NO_3-N concentration: <10 mg L^{-1}	>10 mg L^{-1}	Unknown
Well construction			
Drilled (N = 304)	79%	6%	15%
Sand point (N = 104)	80%	4%	16%
Age of well			
Less than 15 years (N = 199)	79%	3%	18%
15 to 30 years (N = 172)	79%	6%	15%
More than 30 years (N = 69)	72%	10%	17%
Principal land use within a quarter mile of the well			
Agricultural (N = 139) (cropland, pasture, and grassland)	70%	10%*	20%
Non-agricultural (N = 328) (forest, lawn, homes, water, or mixed uses)	82%	3%	15%

*Where the principal land use around the well was agricultural, the odds of elevated well NO_3 concentrations were significantly higher than at other locations, even after accounting for well type, age, and depth (p < 0.01).

Figure 5
"When was your drinking well water last tested for nitrate?"

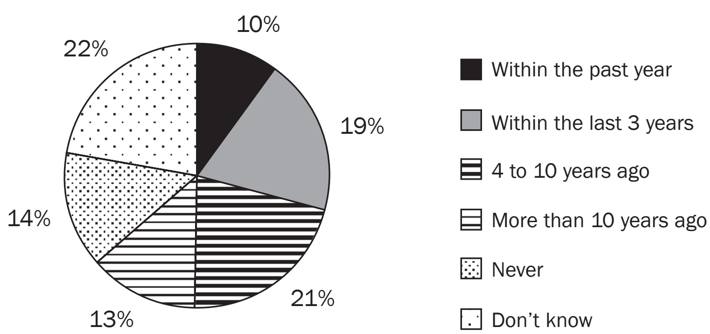
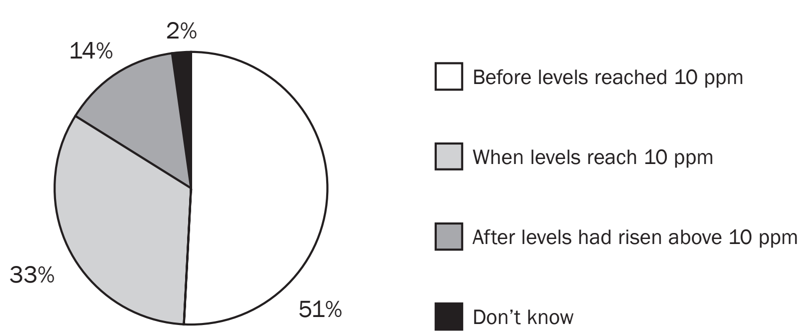


Figure 6
"At what nitrate level would you begin treating your water or finding an alternative source of drinking water?"



Note: Participants were told that the US Environmental Protection Agency considers NO_3-N levels above 10 mg L^{-1} to be unsafe, especially for infants and the elderly.

Table 3
Why don't people test regularly?

Response choice	Percent of respondents
Don't feel a need to have it tested	50%
The water is probably fine	23%
I don't know how to test my water	18%
It is not convenient	9%
Have not had time	9%
It costs too much	4%
Other (didn't know to test; just moved)	18%

Table 4
Responses to elevated nitrate-nitrogen: All well owners.

	Hypothetical actions*	Actual actions			
	N = 471	All respondents *N* = 483	Owners of 0 to 2 mg L^{-1} NO_3-N wells *N* = 299	Owners of >10 mg L^{-1} NO_3-N wells *N* = 33	Increased prevalence associated with NO_3 contamination (col. 4 – col. 3)
	(1)	(2)	(3)	(4)	(5)
Install treatment system	73.9% †	7.5%	6.0%	21.9%	15.9%
Drink bottled water‡	14.4%	10.4%	9.0%	25.0%	16.0%
Install a new well	3.4%	1.7%	0%	25.0%§	25.0%
Nothing	4.7%	83.0%	82.9%	37.5%‖	—
Move	1.5%				

Note: Duplicate responses allowed.

* What respondents said they would do if water NO_3 became unsafe for drinking.

† Including 6% who already have systems.

‡ Only includes those who drink bottled water in response to elevated NO_3. Additional people drink bottled water for other reasons.

§ All eight respondents who said they installed a new well because of elevated NO_3 were included in this high NO_3 group. Water samples submitted for this survey were from their new well and thus had low NO_3 concentrations.

‖ At the time of the survey, most of this group did not know their NO_3-N concentration was >10 mg L^{-1}.

a NO_3 problem may elicit costs even where NO_3 concentrations are not elevated.

Summary and Conclusions

We surveyed a representative sample of private drinking water wells by using a combination of county land parcel lists to identify well owners and a mailed NO_3 test kit. This methodology avoided the high cost of on-site visits. Most people do not test their drinking water on a regular basis because they do not feel a need for testing. Cost and inconvenience were less common explanations for lack of testing. Some were not aware that their carbon filters and water softeners do not remove NO_3. Of the wells tested in this survey, 6% had NO_3-N concentrations >10 mg L^{-1}, and another 5% were between 5 and 10 mg L^{-1}. The proportion of wells with elevated NO_3 was greater where the principal land use within a quarter mile of the well was agricultural versus non-agricultural. Costs of treating or avoiding NO_3 contaminated water can be substantial. Average cost

Table 5
Responses to elevated nitrate-nitrogen: Comparison of well owners who are aware and not aware of their nitrate-nitrogen concentration.

	Hypothetical actions*†		Actual actions					
			All respondents*		Owners of 0 to 2 mg L^{-1} NO_3-N wells		Owners of >10 mg L^{-1} NO_3-N wells*	
	Aware *N* = 106	Not aware *N* = 365	Aware *N* = 106	Not aware *N* = 377	Aware *N* = 46‡	Not aware *N* = 253	Aware *N* = 22	Not aware *N* = 11
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Install treatment system§	87.7*	74.6	14.2*	4.8	13.3*	4.0	27.8*	7.1
Drink bottled water‖	7.5*	16.6	5.7	9.5	4.4	8.9	16.7	21.4
Install a new well	2.8	3.7	7.5*	0	0	0	44.4*#	0
Nothing	1.9*	5.1	72.6	85.7	82.2*	87.0	11.1*	71.4
Move	0	1.9						

Note: No duplicate responses allowed.

* Difference between well owners who are aware and not aware of their NO_3-N concentration is significant (*p*-value < 0.05).

† What respondents said they would do if water NO_3-N concentration became unsafe for drinking.

‡ *N* = 46 is from the 68 people who submitted water samples, not the entire 106 who knew their nitrate concentration.

§ Hypothetical responses includes 9% who already have systems.

‖ Only includes those who drink bottled water in response to elevated NO_3. Additional people drink bottled water for other reasons.

\# Six respondents who said they installed a new well because of elevated NO_3 were included in this high NO_3 group, although water samples submitted for this survey were from their new well and thus had low NO_3 concentrations.

Table 6.
Costs of actions taken in response to elevated nitrate.

	Reported cost average (range)		
	Initial costs	**Annual costs**	**Total annualized costs***
NO_3 removal systems:			
Reverse osmosis: own (*N* = 16 of 25)†	$855 ($85 to $1700)	$87 ($25 to $200)	$130
Reverse osmosis: lease (*N* = 2 of 4)	$0	$360 ($240 to $480)	$360
Distillation (*N* = 4 of 6)	$961 ($190 to $3,000)	Not reported	—
Anion exchange (*N* = 1 of 1)	$1,600	Not reported	—
Weighted average all systems (*N* = 23 of 36)	$798	$100	$140
New well (*N* = 10 of 8)‡	$7,200 ($3,000 to $15,000)	—	$144
Bottled water (*N* = 41 of 50)	—	$190 ($36 to $600)	$190

* Initial cost of treatment systems was divided by the projected 20-year life span of the systems. Cost of a well was divided by 50 years.

† Numbers in parentheses indicate the number of respondents who reported costs and the total number who reported taking that action in response to elevated nitrate concentrations.

‡ Ten respondents reported costs, but only eight installed their well in response to nitrate contamination.

Figure 7
Perceptions of water quality.

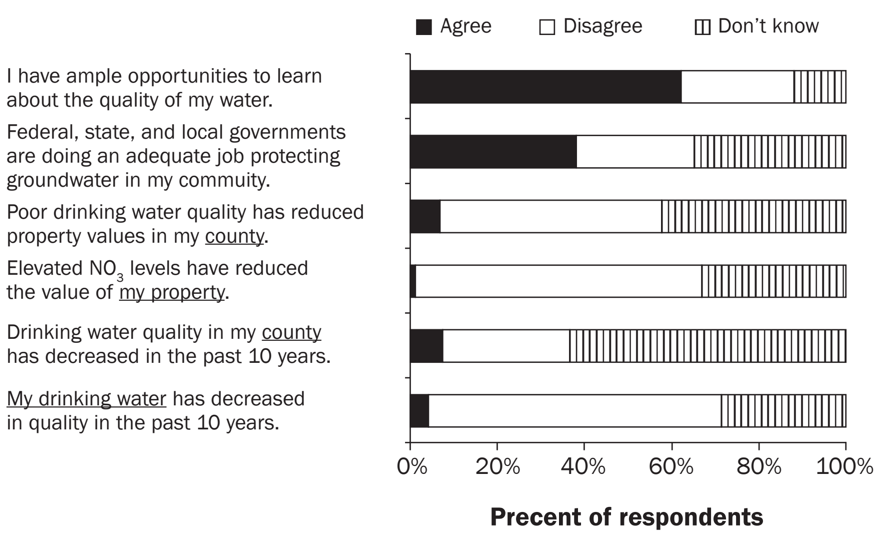
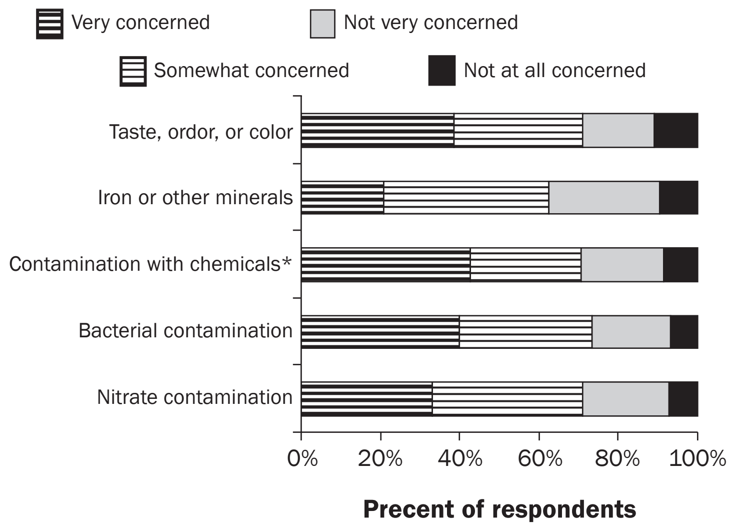


Figure 8
"How concerned are you about the following water quality issues related to your drinking water?"



Note: The sum of respondents who were "very" or "somewhat" concerned was significantly lower for minerals than for other water quality issues (Chi-squared test, $p < 0.01$).

* Actual survey wording was "Contamination with herbicides, volatile organic compounds, or other chemicals."

of a NO_3 removal system was $800 to install and $100 y^{-1} to maintain, and average cost of a new well was $7,200 plus the cost of a water softener in cases where water is drawn from a deep aquifer. If the NO_3-N concentration in an aquifer rose above 10 mg L^{-1}, the one-time average cost per well owner would be $1,927 plus $46 y^{-1}, based on the distribution of responses to elevated NO_3 in this survey. These direct costs of groundwater NO_3 contamination represent the low end of total cost estimates, which should also include non-use values such as the value of knowing a clean aquifer will exist in the future. Quantifying the costs can help justify the expenses associated with protecting groundwater.

Acknowledgements

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Potato Response to a Polymer-Coated Urea on an Irrigated, Coarse-Textured Soil

Melissa L. Wilson, Carl J. Rosen,* and John F. Moncrief

Nitrogen Management

ABSTRACT

Controlled release fertilizers, especially polymer-coated urea (PCU), have been shown to reduce nitrate (NO_3) leaching while maintaining potato (*Solanum tuberosum* L.) yields, but cost has been prohibitive. A new type of PCU (Environmentally Smart Nitrogen, Agrium, Inc., Calgary, AB) is less costly than previous PCUs, but its effectiveness on potato production has not been extensively studied. A 2-yr field study was conducted on loamy sand to evaluate the effect of this PCU on Russet Burbank tuber yield and to determine if it is economically comparable to soluble N sources. Several N rates of PCU applied at emergence were compared with two split applications of soluble N at equivalent rates. Additional treatments examined N application timing of PCU and a fertigation simulation with urea/ammonium nitrate. Petioles and midseason soil samples were collected to determine N status during the season. Overall, PCU and soluble N at equivalent N rates were found to have similar total and grade A yields and net monetary returns. The optimal N rate that resulted in maximum net returns was 251 and 236 kg N ha^{-1} as soluble N and PCU, respectively. Petiole NO_3 concentrations were typically higher with soluble N early in the season and higher with PCU later in the season. Soil NO_3 determined in samples collected in late June was found to be a better predictor of yield and potential N need than those collected in mid- to late July. Overall, PCU may reduce or eliminate the need for split applications of N on coarse-textured soils.

Irrigated potato production has been expanding on coarse-textured soils in Minnesota since the 1960s. In 2007, more than 20,000 ha of potatoes were grown in Minnesota, most of which were produced using irrigation (USDA-NASS, 2007). Potato is considered a high maintenance crop due to its requirement for high nutrient and chemical inputs (Subramanyam, 1993; Guenthner et al., 1999) as well as careful water management. Current practices in Minnesota base N fertilizer additions for potato on crop yield goal and previous crop. For Russet Burbank, a popular processing potato, farmers in Minnesota usually apply 276 kg ha^{-1} of N fertilizer (Bruening, 1996) and supplemental irrigation is supplied by center-pivot. On sandy soils, split applications of N are recommended to reduce leaching (Rosen and Bierman, 2008) including the addition of fertilizer through the irrigation system.

The high input of nutrients for potatoes, coupled with irrigation, has the potential to cause high NO_3 leaching, especially on sandy soils. Irrigated farming has been linked to increasing NO_3 levels in drinking wells and approximately 7% of wells in Minnesota are above the 10 mg L^{-1} NO_3–N level set by the USEPA (O'Dell, 2007; Lewandowski et al., 2008). Introduction of new, cost effective fertilizer technologies into irrigated cropping systems may help to reduce NO_3 leaching while sustaining productivity.

Polymer-coated urea is a type of controlled release fertilizer (CRF) that slowly releases N over time and can be manipulated to match the N needs of specific crops (Shaviv, 2001). Studies on potatoes in Minnesota, Florida, and Colorado fertilized with PCU produced similar or higher yields as those fertilized with ammonium nitrate and urea at equivalent rates (Shoji et al., 2001; Hutchinson et al., 2003; Zvomuya and Rosen, 2001). Zvomuya et al. (2003) found that not only did PCU produce similar or higher potato yields than urea at equivalent rates, but it also increased N use efficiency and reduced NO_3 leaching. Not all types of PCU may be useful for potato production, however. Pack et al. (2006) evaluated nine types of PCU with mixed results on potato yields and fertilizer N removal efficiency.

A major concern with PCU is that until recently, its use was not cost effective due to high prices without a significant return in yield (Trenkel, 1997; Zvomuya and Rosen, 2001). A new type of PCU developed by Agrium Inc., called Environmentally Smart Nitrogen (ESN), is considerably lower in price. Initial studies on potato production in Idaho and Minnesota have shown promising results (Hopkins et al., 2008). The influence of this new PCU on irrigated potato production has not been extensively studied beyond its influence on tuber yield. The objectives of this study were to: (i) determine in situ N release characteristics of the PCU fertilizer, (ii) characterize Russet Burbank potato yield and quality response to N source, rate, and time of application, and (iii) evaluate the economics of using PCU vs. soluble N as the N source.

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Abbreviations: CRF, controlled release fertilizer; CV, critical value; DAP, days after planting; PCU, polymer-coated urea.

MATERIALS AND METHODS

This study was conducted for 2 yr (2006–2007) on different fields at the Sand Plain Research Farm in Becker, MN. The soil at the site is a Hubbard loamy sand (sandy, mixed, frigid Entic Hapludoll) formed in glacial outwash. It is excessively drained, with an available water capacity of 10 cm of water per 152 cm of soil. The previous crop in both years was nonirrigated rye (*Secale cereal* L.). Representative soil samples from 0 to 15 cm were collected in the spring before planting to test for organic matter, P, and K (Brown, 1998), and KCl extractable nitrate N (NO_3–N) and ammonium N (NH_4–N) were determined in 0 to 60 cm samples (Table 1). A WatchDog Model 2800 weather station (Spectrum Technologies Inc., Plainfield, IL) located onsite was used to monitor soil temperature at the fertilizer band depth (approximately 30 cm below the top of the hill) as well as rainfall and air temperature.

Before planting, 280 kg ha^{-1} of potassium-magnesium sulfate and the same rate of potassium chloride were broadcast and then incorporated by moldboard plow. At planting, preweighed starter fertilizer was banded 8 cm to the side and 5 cm below the seed piece using a belt type applicator. Starter fertilizer consisted of potassium-magnesium sulfate, potassium chloride, boric acid, zinc oxide, and either super triple phosphate (for control plots only) or diammonium phosphate (for all other treatments). Total nutrient application at planting included 50 kg P ha^{-1}, 186 kg K ha^{-1}, 33 kg Mg ha^{-1}, 67 kg S ha^{-1}, 2.2 kg Zn ha^{-1}, 0.6 kg B ha^{-1} and an additional 45 kg N ha^{-1} for all treatments except the control.

Russet Burbank was the cultivar chosen for this study and is currently the most popular cultivar used for processing in the upper Midwest. Cut "A" seed on 25 Apr. 2006 and whole "B" seed on 26 Apr. 2007 were hand planted in furrows with 90 cm between rows and approximately 25 cm between seed pieces in the row. Each plot consisted of four, 6 m long rows, with the center two rows used for harvest. Rows were mechanically hilled at plant emergence. Chemicals were applied as needed during the season for the control of pests, disease, and weeds according to standard practices in the region (Egel et al., 2006). Irrigation was applied uniformly across all treatments according to the checkbook method (Wright, 2002). Total N supplied by irrigation was 21.3 and 34.7 kg N ha^{-1} in 2006 and 2007, respectively. Total N supplied by rainfall was approximately 8 kg N ha^{-1} in each year. These amounts were not included in the total amount of applied N reported.

Twelve N treatments (Table 2) were replicated five times in a randomized complete block design. The two sources of N, a 90-d release PCU (ESN, 440 g N kg^{-1}) manufactured by Agrium Inc. and soluble N, were compared across several rates and timing schemes, including rates typically used by farmers in Minnesota (Bruening, 1996). The ESN PCU was obtained directly from the manufacturer and more information about the characteristics of this product can be found in Agrium, Inc. (2005). For treatments 2 to 6, soluble N was split applied at emergence/hilling and at post-hilling. Nitrogen was applied at emergence on 19 May 2006 and 15 May 2007 as urea while the post-hilling application (which occurred on 2 June 2006 and 4 June 2007) was intended to simulate 28% N application: 50% urea and 50% ammonium nitrate was sidedressed and mechanically incorporated into the hill. The post-hilling application for treatment 6 was further split into five applications to simulate fertigation: hand-applied N (urea and ammonium nitrate) was watered-in with irrigation except for the first post-hilling application which was incorporated into the hill. For treatments 7 to 10, PCU was sidedressed at emergence and hilled in. Preplant applied PCU (treatment 11) was broadcast and mechanically incorporated to a depth of 5 to 10 cm approximately 1 wk before planting and PCU was mixed in with starter fertilizer and applied at planting for treatment 12.

Petiole samples were collected on the following dates: 13 and 27 June, 11 and 24 July, and 7 August in 2006; and 12 and 25 June, 9 and 24 July and 6 August in 2007. Twenty or more petioles were collected from the fourth leaf from the terminal in each plot, and were limited to the two center harvest rows. Petioles were dried at 60°C, and then ground with a Wiley mill to pass though a 2-mm screen. Nitrate-N was determined in petiole samples extracted with water (0.1 g in 20 mL of water) using conductimetric procedures (Carlson et al., 1990).

Two midseason soil samples from the upper 30 cm soil depth were collected from each plot on 19 June and 17 July 2006 and on 15 June and 18 July 2007 to determine NH_4–N and NO_3–N concentrations. These samples consisted of five cores across one hill (two at the base, two in the middle, and one at the top) in the harvest rows. Soil samples were air dried and then ground with a chain grinder to pass through

Table 1. Soil properties before spring planting.

	0–15 cm				0–60 cm	
Year	pH	Organic matter	Bray-P	K†	NO_3^-–N‡	NH_4^+–N‡
		%	mg kg^{-1}			
2006	6.6	2.4	32	108	1.1	2.2
2007	6.8	1.5	31	87	1.3	1.8

† Extracted with 1 mol L^{-1} NH_4OAc.

‡ Extracted with 2 mol L^{-1} KCl.

Table 2. Nitrogen treatments for Russet Burbank.

Treatment	Preplanting	Planting	Emergence and hilling	Posthilling†	Total
	kg N ha^{-1}				
1	0	0	0	0	0
N source-diammonium phosphate‡ at planting + soluble N§ after planting					
2	0	45	23	1 x 22	90
3	0	45	68	1 x 67	180
4	0	45	113	1 x 112	270
5	0	45	158	1 x 157	360
6	0	45	115	5 x 22	270
N Source-diammonium phosphate‡ at planting + polymer-coated urea					
7	0	45	45	0	90
8	0	45	135	0	180
9	0	45	225	0	270
10	0	45	315	0	360
11	225	45	0	0	270
12	0	45 + 225	0	0	270

† Posthilling N applications were applied all at once or split into five equal applications over time.

‡ 45 kg N ha^{-1} as diammonium phosphate.

§ Soluble N = urea applied at emergence and urea/ammonium nitrate (1:1) applied at posthilling.

a 2-mm screen. Inorganic N was extracted with a 5:1 ratio of 2 mol L^{-1} KCl to air-dry soil and then filtered. Nitrate-N and NH_4–N were determined in soil extracts using conductimetric procedures (Carlson et al., 1990).

Release rate of N from PCU was determined by burying 3 g of the fertilizer in sealed plastic mesh containers for the three different application timings. Three replications of 10 bags were buried at planting to the depth of the fertilizer band, and approximately 5 to 8 cm below the surface of the hill at plant emergence. For the preplant treatment, mesh bags were buried 5 to 8 cm in the field on the day of fertilizer application, and then transferred to 5 to 8 cm below the surface of the hill after planting. The mesh bags were retrieved periodically throughout the season, placed in a paper bag and air dried. The fertilizer prills were removed from mesh bags by hand, separated from the soil and weighed on a scale. The amount of weight loss was assumed to be equivalent to the amount of N released. This method was shown in a previous study to be comparable to direct measurement of N in the prills (Wilson et al., 2009). Percent of N release (%NR) as a function of time (days after planting) was determined by regression.

Vines were mechanically killed on 19 September in both years, and tubers were machine harvested from the center two rows of each plot approximately 1 wk later. Tubers were sorted into weight classes for total and graded yield. Grade A yield was determined by subtracting undersized (<113 g) tuber yields from the total yield. Twenty-five representative tubers were chosen from each plot to measure incidence of hollow heart (expressed as a percentage of the entire plot) and specific gravity by the weight in air/weight in water method (Dean, 1994).

An economic analysis was conducted to compare net monetary returns of each N treatment. Prices, incentives, and penalties were based on a typical potato growing contract between grower and a food company in Minnesota. The base price for grade A tubers (>113 g) was $0.056 per kg, and tubers <113 g received a price of $0.013 per kg. Incentives or penalties were based on specific gravity and the percent of total tuber yield >170 g. For specific gravity below 1.076 the base price was reduced, and between 1.080 and 1.090 the base price was increased. Incentives were granted when 55% or more of the total tuber yield was above 170 g, although the incentive decreased after 68% was above 170 g. Penalties were deducted when 53% of the tuber yield was below 170 g. Net monetary return was calculated based on gross value of the potato crop minus the cost of the fertilizer and its application cost. Urea was priced at $1.34 per kg N, PCU at $1.54 per kg N, while urea/ammonium nitrate for the fertigation simulation was $1.45 per kg N. Application costs were estimated by an agronomist with a local grower. At emergence and sidedress, application cost for urea was approximately $44 per hectare, the PCU cost at preplant and emergence was $22 per hectare, while the total cost of the five fertigation treatments was $59 per hectare. The cost of applying PCU at planting was assumed to be $0 since it was simply mixed in with starter fertilizer.

Data from the study were analyzed using PROC MIXED (SAS Institute, 2004) with replications and years considered as random variables. Differences among treatments in years (the year × treatment interaction), were assessed by year-specific inference using best linear unbiased predictors (BLUPs) as described by Littell et al. (2006). For petioles, years were analyzed separately for each sampling date. Treatment means were compared using the least-square means (SAS Institute, 2004). For evaluating PCU release rate characteristics, as well as PCU effects on total and grade A yields, and the economic analysis, regression models were fit for each treatment or N source and analyzed in PROC MIXED, while final regression equations were estimated by PROC REG (SAS Institute, 2004).

Soil inorganic N was related to tuber yield to determine the use of soil N tests as a predictor of potential in-season N needs by potato. Tuber yields were expressed as relative yields to standardize the relationship between years and were calculated as the ratio between yield and the maximum yield of each corresponding year. PROC NLIM was used to determine the quadratic plateau model that related total inorganic N (NH_4–N + NO_3–N), NH_4–N and NO_3–N to total and grade A yields (SAS Institute, 2004). This method does not calculate R^2 values, so the following equation was used:

$$R^2 = (\mathrm{CTSS} - \mathrm{SSE})/\mathrm{CTSS}$$

where R^2 is the fraction of the variation in the dependent variable as explained by the model, CTSS is the corrected total sums of squares, and SSE is the sums of squares of the error found in the PROC NLIM output (Robbins et al., 2006).

RESULTS AND DISCUSSION

Weather

Mean temperature and rainfall for the 2006 and 2007 growing seasons (April through September) are compared with 30 yr averages for Becker, MN in Table 3. The 52 cm of total rainfall in 2006 was supplemented by 39 cm of irrigation for a total of 94 cm of water. In 2007, approximately 48 cm of irrigation was applied in addition to 45 cm of rainfall for a total of 103 cm of water over the growing season. Overall, 2006 and 2007 were warmer and drier than the average growing season. A precipitation deficit of 3.3 and 9.8 cm occurred in 2006 and 2007, respectively, although the crop received approximately 9 cm of additional irrigation water in 2007 compared with 2006. Higher irrigation amounts used in 2007 were intended to ensure that some leaching occurred and to minimize misshapen tubers, which can occur

Table 3. Mean monthly rainfall and air temperature data for 2006 and 2007 growing seasons and the 30-yr mean.

	Rainfall			Temperature		
Month	2006	2007	30-yr mean†	2006	2007	30-yr mean†
	cm			°C		
April	9.4	3.9	6.0	10.5	6.7	7.2
May	10.8	7.5	8.2	14.3	16.4	14.5
June	4.9	3.2	11.3	19.6	21.0	18.9
July	4.5	4.9	10.5	24.3	22.9	21.5
August	9.1	13.0	11.8	19.7	20.8	20.1
September	13.0	12.8	7.4	13.6	16.9	14.9

† Average for the 30-yr period from 1971 to 2000.

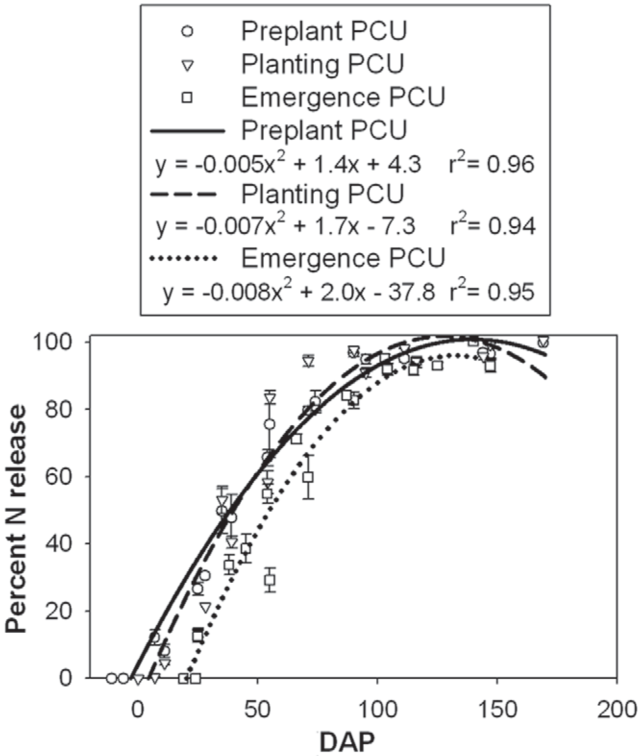

Fig. 1. Percentage of N release from polymer-coated urea (PCU) incubated in the potato hill as a function of the number of days after planting (DAP). Means are presented with standard error bars.

with water stress (Shock et al., 2007). In 2006, the average temperature over the growing season was 0.8°C above average and it was 1.3°C above average in 2007.

Nitrogen Release Rate from Polymer-Coated Urea

Quadratic models effectively described PCU N release characteristics when data were pooled over the 2-yr study (Fig. 1). Each timing treatment was found to have a separate quadratic model after an analysis of regression determined that slopes and intercepts were significantly different ($P < 0.05$). Intercepts differed due to the timing of application; planting and preplant PCU were applied approximately a week apart, while emergence PCU was applied about 3 wk after planting. Emergence applied PCU had the steepest slope, which indicates a quicker release pattern, and PCU applied at preplant had the lowest slope. When soil moisture is not limiting, the release rate of N from PCU is mainly determined by soil temperature (Salman et al., 1989; Gandeza et al., 1991). Therefore the difference in slopes may be due to warmer temperatures during the initial N release from emergence applied PCU. The equations indicate that 90% of N had released by 93, 86, and 104 d after planting (DAP) for preplant, planting and emergence applied PCU, respectively. Approximately 100% of N from PCU was released by 110 and 125 d after planting for preplant and planting applied PCU, while PCU applied at emergence had released more than 95% of N by vine harvest at 147 DAP.

The release rate of any controlled release fertilizer (CRF) must be matched with crop uptake to optimize N use efficiency, but some CRFs have been found to release N past the growing season (Cox and Addiscott, 1976; Zvomuya et al., 2003). Pack (2004) tested several PCUs with the potential to match potato N uptake and found mixed results; some PCUs had released more than 80% by 100 DAP, while others had only released 60%. For PCU in this study, more than 90% of the N had been released by 100 DAP regardless of application timing, and suggests it is a good match for N uptake of long season crops such as Russet Burbank potato under Midwest U.S. conditions.

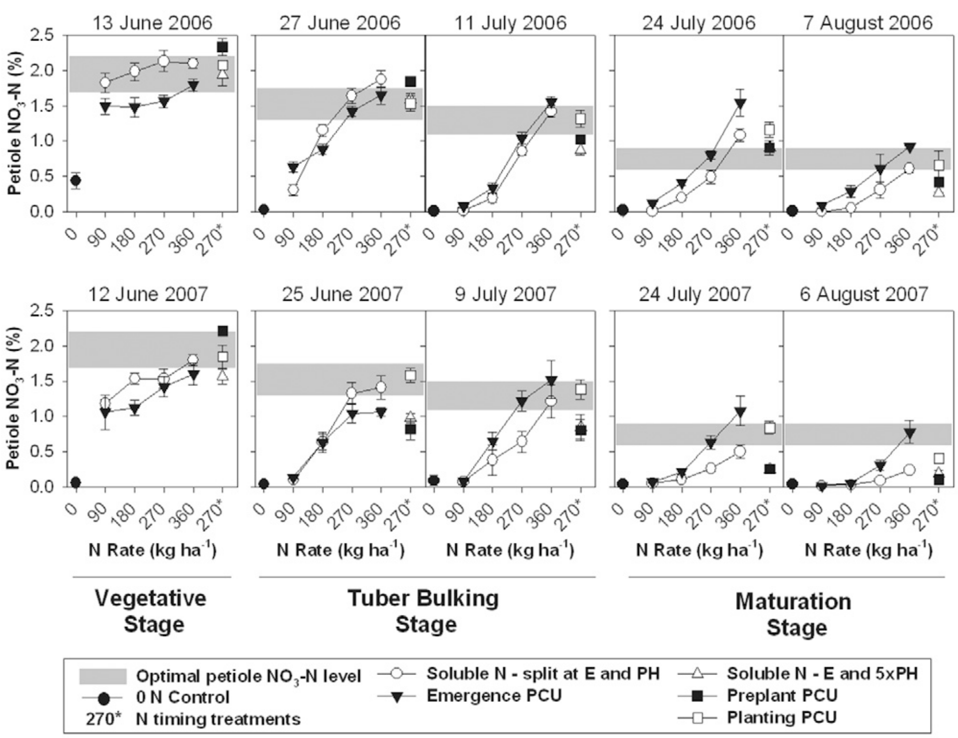

Fig. 2. Petiole nitrate concentrations over five sampling dates in 2006 and 2007 as affected by N rate, source, and timing. The two N sources included soluble N split applied at emergence (E) and posthilling (PH) and polymer-coated urea (PCU) applied in a single application at preplant, planting or emergence. Means are presented with standard error bars.

Petiole Nitrate Concentrations

In both years, petiole NO_3–N concentrations generally decreased as the season progressed and increased as N rate increased regardless of N source (Fig. 2). The addition of N significantly increased petiole NO_3–N concentrations on the first sampling date during both years, and on the second date in 2006. On the remaining sampling dates in 2006, petiole NO_3–N concentrations for soluble N treatments at 180 kg N ha^{-1} or less were not significantly different from the 0 N control, while only the lowest rate of PCU showed this pattern. In 2007, this same pattern had developed by the second sampling date, but on the last date only 360 kg N ha^{-1} of soluble N resulted in significantly higher petiole NO_3–N than the control, while both PCU at 270 and 360 kg N ha^{-1} were significantly higher than the control.

On some dates, timing of N application significantly affected petiole NO_3–N concentrations, particularly early and late in the season. During both years, the highest petiole NO_3–N concentrations for 270 kg N ha^{-1} as PCU on the first date were found with the preplant PCU treatment, followed by planting PCU and the lowest was with emergence PCU (all significantly different, $P < 0.05$). In 2006, all petiole NO_3–N concentrations were approximately the same on the last sampling dates, but in 2007, preplant PCU resulted in significantly lower petiole NO_3–N than PCU applied at planting or emergence from the third sampling date through the rest of the season. In both years, PCU applied at planting resulted in significantly higher petiole NO_3–N than PCU at emergence only on the first sampling dates. During 2006, six splits (E and 5xPH) and two splits (E and PH) of soluble N resulted in similar petiole NO_3–N concentrations, except on the fourth sampling date in late July where significantly higher NO_3–N concentrations were found with six splits of soluble N. The fourth petiole sampling date occurred 10 d after the last N application of the six split treatment. In 2007, the six split soluble N treatment typically resulted in higher petiole NO_3–N concentrations later in the season than the two split soluble N treatment. Although these differences were not significant, petiole NO_3–N with six splits of soluble N was significantly higher than the control on the last sampling date while petiole NO_3–N with the two split soluble N treatment was not.

Contrasts were used to compare N sources across equivalent rates (treatments 2, 3, 4, and 5 vs. 7, 8, 9, and 10). Overall, soluble N treatments resulted in significantly higher petiole NO_3–N concentrations for the first two sampling dates, while PCU resulted in significantly higher concentrations for the remaining dates, displaying its slow N release characteristics. These results differ from a study in Florida where the authors reported no differences in petiole sap NO_3–N with several types of PCU and ammonium nitrate throughout the season (Pack et al., 2006). Only two N rates were tested, however, and that study was only conducted over 1 yr.

Petiole NO_3–N concentration is a widely accepted method to determine potato plant N status during the growing season (Porter and Sisson, 1991; Belanger et al., 2003; Rodrigues, 2004). Rosen and Eliason (2005) have listed optimal ranges for petiole NO_3–N concentrations in the Upper Midwest depending on the growth stage of the potato plant and are highlighted in gray in Fig. 2. The preplant PCU treatment resulted in excessive petiole NO_3–N levels early on in both years, and then fell to deficient levels for the remainder of the season. Petiole NO_3–N with planting PCU and both N sources at 360 kg N ha^{-1} were within or above optimal levels for the entire season in 2006. Petiole NO_3–N with emergence PCU at 270 kg N ha^{-1} was also within or slightly below the NO_3–N concentration range during the tuber bulking and maturation stages (sampling dates 2–5). In 2007, petiole NO_3–N with the planting PCU treatment was only deficient on the last date, while 360 kg N ha^{-1} of soluble N treatment resulted in petiole NO_3–N concentrations remaining within the sufficiency range on the first three dates while the equivalent rate of PCU was within range on the last three dates. This again illustrates the slow release nature of N with PCU. Other treatments occasionally were within the petiole NO_3–N sufficiency range, but never for more than two sampling dates in the season. Traditionally, petiole NO_3–N concentrations below the optimal limit would trigger an additional application of N. Due to the slow release nature of N with PCU, however, petiole NO_3–N concentrations are often within the sufficiency ranges at the end of the season, and additional N would most likely be unnecessary.

Midseason Soil Inorganic Nitrogen

Soil NO_3 tests during the growing season have successfully been used in corn to predict the nutritional needs of the crop grown on various soil types (Fox et al., 1989; Meisinger et al., 1992; Andraski and Bundy, 2002), but fewer studies have been conducted on potato. Total inorganic N, NH_4–N, and NO_3–N were related to total and grade A yields for each N source in June and July of the potato season by a quadratic plateau model (Fig. 3). The critical value (CV) is defined as the point on a curve that relates the soil N to the yield; below or above this point there is a high probability that the crop responds (below) or not (above) to supplementary applications of N (Rodrigues, 2004). This point on a quadratic plateau model is where the quadratic line intersects the linear line. Treatment 6, or six applications of soluble N, was removed from the analysis because not all N had been applied by either June or July sampling dates.

In June, the soil component that best modeled the CV was NO_3–N for both total and grade A yields as seen by the highest R^2 values for both soluble N and PCU. The R^2 values were generally higher for soluble N than PCU. The quadratic plateau model poorly fit NH_4–N and total N data for both N sources. All R^2 values were below 0.06 for the July soil samples, or the model could not be calculated for the data presented. Typically under Midwest conditions, Russet Burbank potato has only accumulated 50% of its total N uptake by mid-June (approximately 53 DAP) while in mid-July (approximately 83 DAP), the crop has taken up more than 90% of N (Zebarth and Rosen, 2007). This suggests that soil nitrate or ammonium tests in mid-July would not provide accurate estimates of potato N needs since most of the N has already been taken up by the crop.

Belanger et al. (2001) and Rodrigues (2004) also found that soil NO_3–N was the best method for potato, and that the inclusion of NH_4–N did not improve the test. Meisinger et al. (1992), however, found that the addition of soil NH_4–N was advantageous to determining the CV for corn yields and suggested that it more accurately represented the total availability of N to the crop. The results presented in Belanger et al. (2001) and in the current study were based on dry soil samples, while field moist soil samples were used in Rodrigues (2004). The comparable results between studies suggest that this test will be accurate regardless of the method used for soil sampling.

The NO_3–N CV in June for soluble N was higher than that for PCU for both grade A and total yields. At equivalent N rates, soil NO_3–N in June was higher with soluble N than PCU (Table 4) and reflects the slow N release characteristics

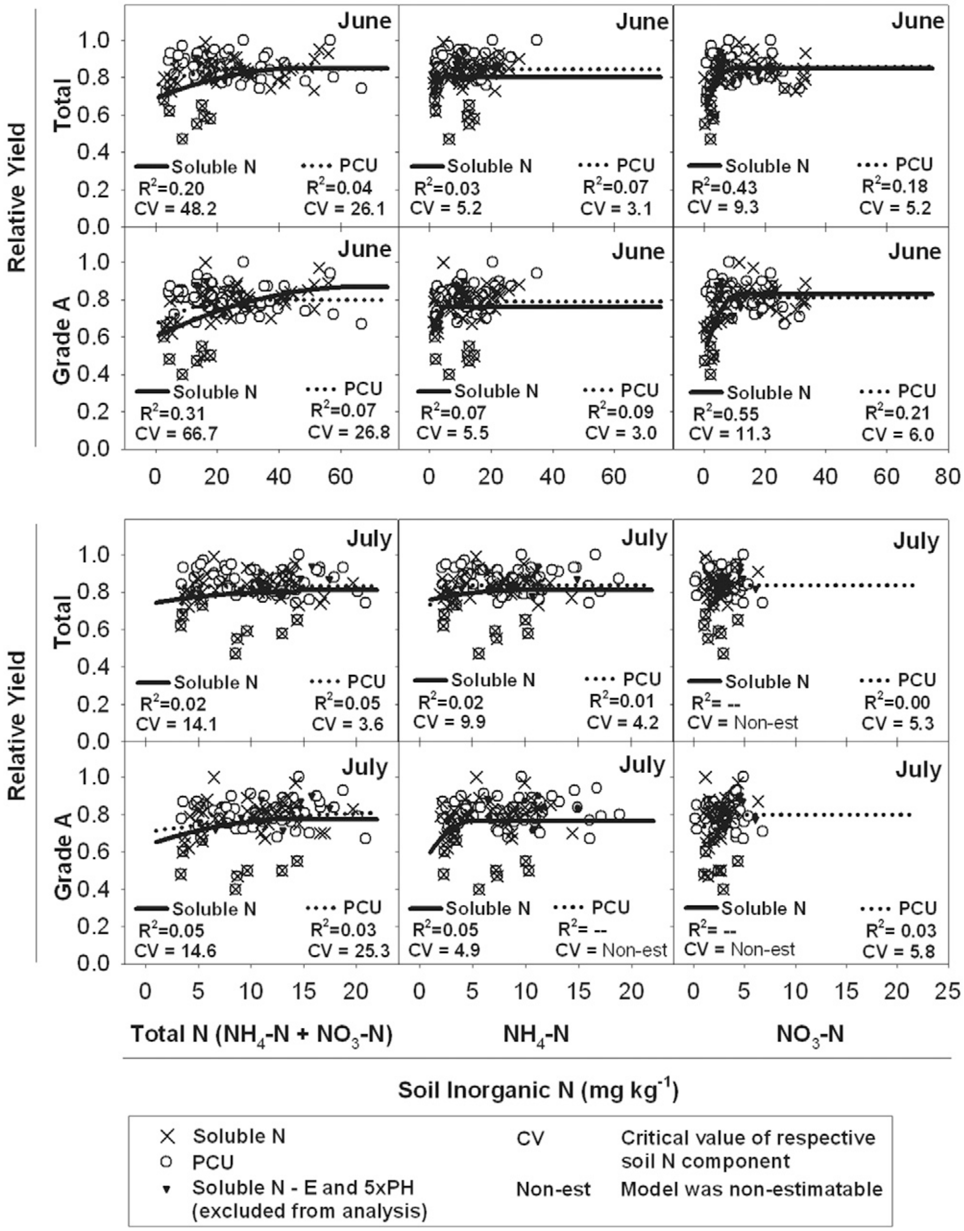

Fig. 3. The relationship between soil inorganic N in the top 30 cm and relative yield over 2 yr as described by a quadratic plateau model. The two N sources included soluble N and polymer-coated urea (PCU). The treatment in which soluble N was split applied six times [at emergence (E) and five times at post-hilling (5xPH)] was not included in this analysis since all N applications had not occurred before the soil sampling dates.

the NO_3–N concentration for the six split soluble N treatment (10.5 mg kg^{-1}) was less than the critical CV for grade A yields (11.3 mg kg^{-1}) suggesting that additional N was needed.

Belanger et al. (2001) recommended a CV of 80 mg NO_3–N kg^{-1} soil between 37 and 42 DAP for grade A Russet Burbank and Shepody potato yields in Atlantic Canada. This level is much higher than levels suggested in the current study for 50 to 55 DAP (11.3 and 6.0 mg NO_3–N kg^{-1} soil for soluble N and PCU, respectively), and may be due to several factors. In Belanger et al. (2001), potatoes were fertilized only at planting and the soil samples were taken earlier in the season when there was less N uptake by the crop. That study was also conducted on a finer-textured soil where soil NO_3 was less likely to be leached or diluted. Rodrigues (2004) provided a model for continuous CVs during the growing season and the proposed CV for the time that corresponded with our sampling dates was 15.3 mg NO_3–N kg^{-1} soil. This value is similar to the CV presented in the current study, and may be due to similar soil conditions (coarse-textured soils). The slightly higher CV, however, may be due to differences in N application timing and climatic conditions. Potatoes in that study were fertilized with split N applications at preplant and emergence and were grown under Mediterranean conditions. The differences between the three studies suggest that CVs may vary over soil type, fertilizer management practices and climatic patterns and that it is important to determine CVs for the growing conditions in local potato production areas.

of the PCU. This demonstrates that N source must be taken into consideration when using a soil N test. Both N sources had higher CVs for grade A tuber yields than for total yields. Because grade A yield is total yield minus small tubers (<113 g), the higher CV for grade A yield indicates that higher soil NO_3–N levels are needed to produce larger tubers. In addition,

Table 4. Effect of year on Russet Burbank yields, tuber quality, and soil inorganic N (0–30 cm).

	Harvest			Quality	
Year	Total yield	Grade A yield	Tubers in total yield >170 g	Specific gravity	Hollow heart
	Mg ha^{-1}		%		%
2006	71.6 b†	56.3 b	51.9 b	1.083 a	5.9 a
2007	77.5 a	66.9 a	63.7 a	1.075 b	7.1 a

† Means followed by the same letter are not significantly different (*P* > 0.05).

Tuber Yield and Size

While there were no significant interactions between year and N treatment, there was a significant effect of year on tuber yields. Higher total and grade A yields were produced in 2007 than in 2006, and the percentage of tubers >170 g was also higher in 2007, even in the controls (Table 4). This suggests that the yield difference between years was probably due to weather conditions that allowed the greater bulking of tubers. In 2007, irrigation was used more often due to lower precipitation and higher temperatures. More frequently scheduled irrigation allows for less variability in soil moisture, which is important for tuber bulking. Several studies have shown that more frequent irrigations increase large tuber yield (Saffigna et al., 1977; Alva et al., 2002).

Nitrogen treatments significantly affected total and grade A yields (Fig. 4). In both cases, the addition of N resulted in significantly higher tuber yields than the 0 N control, but differences between N sources at equivalent N rates were insignificant. There were also no differences in grade A and total yields due to varying the application timing of N. In the past, controlled release fertilizers have performed poorly compared with soluble N sources (Leigel and Walsh, 1976; Waddell et al., 1999) due to unpredictable release patterns. By coating urea with a polymer, manufacturers have greater flexibility in designing PCUs with release rates that match the uptake of specific crops (Trenkel, 1997). Our findings and other recent reports have found that certain PCUs can produce similar or greater yields than soluble N at equivalent rates (Shoji et al., 2001; Hutchinson et al., 2003; Zvomuya et al., 2003; Hopkins et al., 2008).

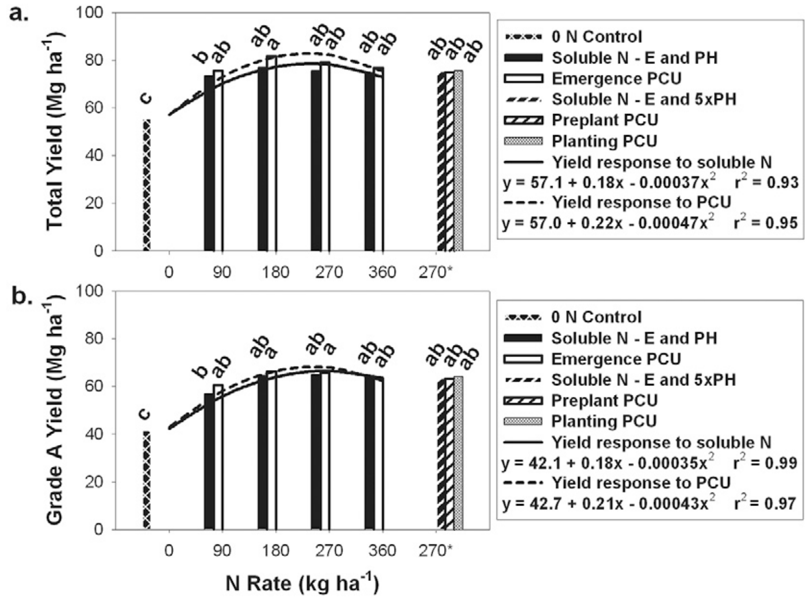

Fig. 4. Response of (a) total and (b) grade A tuber yields as affected by N rate, timing, and source. In each graph, yields with the same letters are not significantly different (*P* > 0.05). The two N sources included soluble N split applied at emergence (E) and posthilling (PH) and polymer-coated urea (PCU) applied in a single application at preplant, planting, or emergence. The 270* refers to N timing treatments.

Regression equations were used to determine total and grade A yield response to N rate (Fig. 4). This analysis excluded N timing treatments 6, 11, and 12 due to the lack of comparable treatments with both N sources. Quadratic equations were found to model the response, which implies that excessive N caused a decline in tuber yields. Belanger et al. (2000) also found that quadratic models were best suited to model potato yield response to N fertilization. Slopes and intercepts were not significantly different between N sources for either total or grade A yields. The equations indicate that maximum total yields occurred at 234 kg N ha^{-1} of PCU and 239 kg N ha^{-1} of soluble N, respectively. For maximum grade A yields, however, 244 and 266 kg N ha^{-1} of PCU and soluble N were needed, respectively. This suggests that slightly reduced N rates with PCU can produce maximum grade A yields compared with soluble N, but since the regression lines for each N source are not significantly different, optimal N rates for the two N sources cannot be assumed different.

The proportion of tubers above 170 g was significantly affected by N treatment (data not shown). An increase in N rate typically increased the percentage of tubers >170 g, although differences between N rates were not always significant. This size class is of economic importance because growers receive incentives or are deducted penalties based on the percentage of tubers in this category. At equivalent N rates, differences were not found between N sources. In other studies, however, PCU was reported to increase the proportion of large tubers compared with soluble N (Zvomuya and Rosen, 2001; Zvomuya et al., 2003).

Tuber Quality

The incidence of hollow heart was significantly affected by N treatment ($P < 0.05$) (Table 5) but there was no significant effect of year or an interaction between year and N treatment. The addition of N significantly increased the percentage of tubers affected by hollow heart over the 0 N control. Soluble N applied six times resulted in the highest incidence of this deformity, but it was only significantly higher than two split applications of soluble N at the lowest N rate (90 kg N ha^{-1}) and emergence PCU at 270 kg N ha^{-1}. Hollow heart typically affects larger tubers (Beattie, 1989), and the addition of N generally increased the proportion of tubers above 170 g. Zvomuya and Rosen (2001) found that hollow heart was not significantly affected by N rate, but a 0 N control was not used in their study.

A significant difference between years was found for specific gravity ($P < 0.05$) (Table 4). Nitrogen treatments did not significantly affect specific gravity, indicating that factors

Table 5. Incidence of hollow heart as affected by N rate, source, and timing. Nitrogen sources include soluble N and polymer-coated urea (PCU).

Treatment no.	N source	N rate†	Timing PP, P, E, PH‡	Hollow heart§
				%
1	none	0	0, 0, 0, 0	0.8 d
2	soluble N	90	0, 45, 23, 22	2.4 cd
3	soluble N	180	0, 45, 68, 67	7.2 ab
4	soluble N	270	0, 45, 113, 112	7.6 ab
5	soluble N	360	0, 45, 158, 157	9.2 ab
6	soluble N	270	0, 45, 115, 5x22	10.1 a
7	PCU	90	0, 45, 45, 0	6.5 abc
8	PCU	180	0, 45, 135, 0	6.4 abc
9	PCU	270	0, 45, 225, 0	4.8 bcd
10	PCU	360	0, 45, 315, 0	8.4 ab
11	PCU	270	225, 45, 0, 0	6.8 abc
12	PCU	270	0, 270, 0, 0	7.6 ab

† N rate is in kg N ha^{-1}; 45 kg ha^{-1} of N at planting is from diammonium phosphate.

‡ PP, P, E, PH = preplanting, planting, emergence and hilling, and posthilling, respectively.

§ Means followed by the same letter are not significantly different ($P > 0.05$).

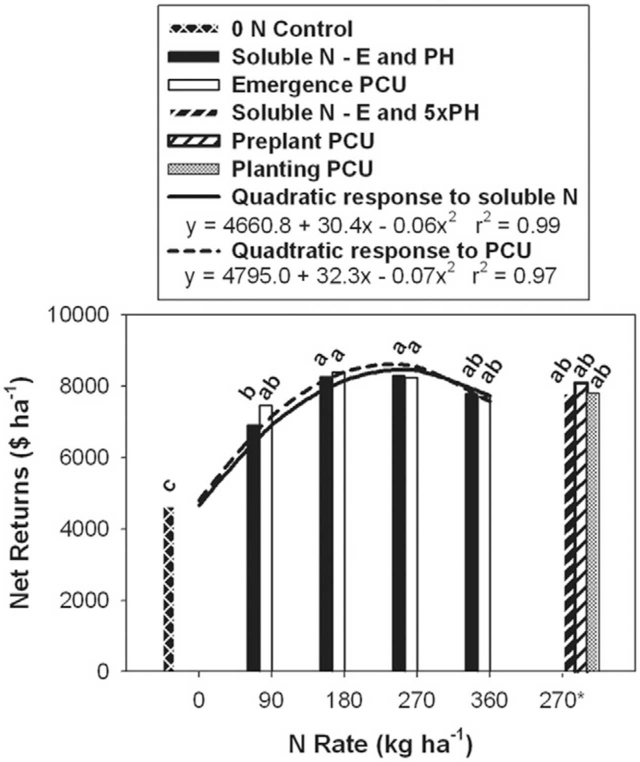

Fig. 5. Effect of N rate, timing, and source on net return of irrigated Russet Burbank potato. Mean returns with the same letter are not significantly different (*P* > 0.05). The two N sources included soluble N split applied at emergence (E) and posthilling (PH) and polymer-coated urea (PCU) applied in a single application at preplant, planting, or emergence. The 270* refers to N timing treatments.

differing between years, such as temperature or irrigation, may have played a role in producing tubers with a lower specific gravity in 2007. This is contrary to the findings of Belanger et al. (2002) who reported that specific gravity was affected by N fertilization and not irrigation. Several other studies however, have shown a reduction in specific gravity can be caused by higher temperatures (Van den Berg et al., 1990) or increased irrigation (Porter et al., 1999; Yuan et al., 2003), both of which occurred in 2007 compared with 2006. There was not a significant interaction between years and N treatments.

Economic Analysis

A simple economic analysis was determined for each treatment and year to compare monetary returns from potatoes fertilized with PCU with those fertilized with soluble N. Overall, N treatments significantly affected net returns (Fig. 5), but the interaction between year and N treatment were nonsignificant. Response curves to N rate were also determined for each N source, but this analysis excluded N timing treatments (6, 11, and 12) which did not have equivalent treatments for both N sources. As expected, significantly higher net returns occurred with the addition of N over the 0 N control, and there were no significant differences in returns between soluble N and PCU at equivalent N rates, including N timing treatments. This suggests that the use of PCU could reduce or eliminate the need for fertigation. Returns were significantly higher in 2007 (\$8135 ha^{-1} compared with \$7098 ha^{-1} in 2006), due to higher yields and more tubers above 170 g.

The effect of N rate on net returns fit a quadratic model. No differences between slopes or intercepts were found due to N source. It is important to note that an increase in N over the optimum rate generally decreased net returns. Based on quadratic models, the maximum net return was at 251 and 236 kg N ha^{-1} for soluble N and PCU, respectively. These optimal rates differ from those calculated from total and grade A yields, because the calculation of net return takes into account total and grade A yields, as well as tuber quality. This technique may be a better predictor of optimal N rate than total or grade A yields alone, but could change as incentives for tuber size and quality change. These N rates are slightly below the traditional N rates (~ 270 kg N ha^{-1}) recommended in Minnesota (Bruening, 1996), which may in part be due to relatively low leaching events in the current study.

CONCLUSIONS

This 2-yr study has shown that total and grade A potato yields with the PCU evaluated were similar to those with split applications of soluble N, even though weather conditions were hotter and drier than average. Based on fertilizer prices and application costs, we have also found that the net returns with PCU were comparable with those for soluble N, and that PCU may reduce or eliminate the need for fertigation and associated management costs. Traditionally, PCU was at least four times the cost of basic soluble N (Trenkel, 1997), and even with increases in yields, PCU use was not considered an economical option (Zvomuya and Rosen, 2001). Most economic analyses, including our own, do not take into consideration environmental costs. With the potential of PCU to reduce NO_3 leaching compared with soluble N (Wilson, 2008) along with the need for only one application, this particular brand of PCU may be more attractive to potato growers than traditional fertilizers.

ACKNOWLEDGMENTS

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Kidney bean (*Phaseolus vulgaris* L.) production on an irrigated, coarse-textured soil in response to polymer coated urea and tillage: I. Grain yields, disease severity, and a simple economic analysis

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ABSTRACT

Kidney beans (*Phaseolus vulgaris* L.) in Minnesota are commonly grown on irrigated, coarse-textured soils that are susceptible to nitrate leaching. A dense Bt layer that is present in these soils restricts root growth and may increase severity of *Fusarium* root rot. Anecdotal evidence from local growers suggests that breaking up the Bt layer reduces the impact of root rot. This study was conducted to assess different tillage depths and the use of polymer coated urea (PCU, Agrium U.S. Inc. and WSPCU, Specialty Fertilizer Products) on grain yields, net monetary returns and disease severity. The study was conducted over three years as a split plot design. Whole plots were deep and shallow tillage (chisel plowed to an average of 47 and 29 cm, respectively) while N treatments were subplots. Three rates of PCU applied at emergence were compared with equivalent rates of urea split applied at emergence and prebloom. Also, one rate of each source, including WSPCU, was applied at planting and a 0 N control was included. Differences between tillage depths were not found. Disease severity was not significantly affected by tillage depths or N treatment. Emergence applied PCU resulted in lower grain yields and monetary returns than split urea applications. PCU applied at planting, however, resulted in similar yields and monetary returns compared with split and planting urea, which suggests a more optimal N regime for kidney bean production. Planting applied WSPCU also resulted in similar yields and net returns as planting applied urea.

Keywords: kidney bean, polymer coated urea, nitrogen rate, tillage, disease severity, yield and economic analysis.

INTRODUCTION

Dry edible beans are an important agronomic crop in the United States. Minnesota, one of the top five bean producing states in the country, is currently the leading producer of dark red kidney beans (*Phaseolus vulgaris* L.) (NASS, 2004). In 2007, approximately 59 thousand hectares of beans were harvested in the state (NASS, 2007). Dry bean production is comparatively new to Minnesota, relative to other bean producing areas, with large scale production beginning in the 1970s (McMartin et al., 1982). Dry beans are typically grown in areas with well drained soils, although irrigation is often needed to ensure that 2.5-3.8 cm of water every 4-5 days are provided (Egel et al., 2008). Dry beans are a short season crop, with plants typically reaching maturity in 90 - 100 days, depending on the variety. In Minnesota, the crop is sown in late May and harvested in early September.

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Dry beans have special management needs due to their limited ability to fix nitrogen and high susceptibility to disease. A symbiotic relationship with *Rhizobium phaseoli* allow dry beans to fix nitrogen, although as a species they are poor at it compared with other legumes (Piha and Munns, 1987). For instance, on average dry beans fix a total of 85 kg N_2 ha^{-1} while soybeans fix 248 kg N_2 ha^{-1} (Unkovich and Pate, 2000). Nitrogen fixation may be limited by several factors alone or more often in combination: low levels of micronutrients, competition with native (but usually ineffective) soil rhizobia, and high inputs of N which tend to inhibit fixation (Graham and Ranalli, 1997). Studies have shown that inoculation of dry beans with effective rhizobia helps with nitrogen fixation and increases yields (Duque et al., 1985; Da Silva et al., 1993; Camacho et al., 2001), but yields were not affected in the Upper Midwest (Weiser et al., 1985). Even when inoculated, some studies have found higher yields with the addition of N fertilizers (Edje et al., 1975; Henson and Bliss, 1991). Current N fertilizer recommendations for coarse textured soils in Minnesota are to apply a total of 45-68 kg N ha^{-1} (depending on yield goal) at emergence and prebloom (Rehm et al., 1995).

Fusarium root rot of dry beans is a widespread disease that has had a significant impact on production (Hall, 1996). In Minnesota, root rot is often caused by *F. solani* f. sp. *phaseoli* in complex with *R. solani* and *F. oxysporum* and yield losses due to this disease can be up to 50% (Estevez de Jensen, 2000; Estevez de Jensen et al., 2002). The increasing incidence and severity in this area has been attributed to shortening of rotation intervals, increased acreage, heavy N fertilization and the use of highly susceptible cultivars (Estevez de Jensen et al., 2004). In Central Minnesota, dry beans are typically produced on irrigated coarse textured soils that have a well defined Bt layer with increased bulk density and reduced hydraulic conductivity (Sexton et al., 1996). A Bt horizon can be restrictive to root growth and often aggravates root rot by confining the pathogen to the plow layer (where roots are also concentrated) and by allowing for the buildup of soil moisture in the root zone (Burke et al., 1972; Allmaras et al., 1988). While several studies have shown that breaking up a restrictive layer through tillage can increase yields and reduce disease severity (Burke et al., 1972; Harveson et al., 2005), there is only anecdotal evidence in Minnesota.

Current recommendations for coarse textured soils in Minnesota include N fertilizer applications, even though fertilizer N recovery is often low (<50%) (Rennie and Kemp, 1983; Tsai et al., 1993; Kipe-Nolt and Giller, 1993). This in combination with additional N supplied by biological N fixation and unpredictable rain increases the potential of nitrate (NO_3) leaching to groundwater. Breaking up of the Bt layer may further exacerbate the NO_3 leaching problem by increasing water percolation beyond the root zone.

Controlled release fertilizers are one option to reduce NO_3 leaching while maintaining yields by matching the release of N to plant uptake. Sulfur coated ureas (SCU) have shown mixed results on potatoes and corn. In a severe leaching year, corn yields were similar and potato yields were higher when fertilized with SCU compared with urea, but yields and N recovery for both corn and potato were significantly reduced when fertilized with SCU under normal weather conditions (Leigel and Walsh, 1976). Polymer coated ureas (PCU), however, have more predictable release patterns than SCU (Trenkel, 1997) and have resulted in similar or higher yields in potato and rice compared with soluble N sources (Shoji et al., 2001; Hutchinson et al., 2003; Carreres et al., 2003).

While studies have shown promising results with PCU, producers have been hesitant to adopt the fertilizer due to high prices (Trenkel, 1997; Zvomuya and Rosen, 2001). Recent advances have significantly lowered production costs and a new brand of PCU, called Environmentally Smart Nitrogen (ESN; Agrium U.S. Inc), is competitively priced with other N fertilizers. With potato, this PCU resulted in similar yields compared with untreated N sources (Hopkins et al., 2008; Wilson, 2008). The effect of any PCU on dry bean production has not been previously reported.

The overall objectives of this study were to compare several variables on dry bean yields, disease severity and net monetary returns, including: 1) deep tillage versus shallow tillage (breaking up the Bt horizon versus not), 2) PCU versus untreated urea at varying N rates and timing of application, and 3) interactions between tillage depth and N treatments.

METHODS AND MATERIALS

A preliminary field experiment conducted in 2005 and a two-year field study from 2006 – 2007 were conducted at the Central Lakes College Agricultural Irrigation Experiment Station near Staples, MN. This site had a past history of severe root rot and soil was naturally infested with *Fusarium oxysporum*, *F. solani* f. sp. *phaseoli*, and *Rhizoctonia solani* AG-4 (Estevez de Jensen et al., 2004). The soil at the site is a somewhat excessively drained Verndale sandy loam (frigid Typic Argiudoll), with a 17 cm thick Bt layer beginning at approximately 25 cm below the top of the soil. Sexton et al. (1996) reported that bulk density of the Ap, Bt and C horizons ranged from 1.5-1.7 Mg m^{-3}, 1.6-1.9 Mg m^{-3}, and 1.5-1.6 Mg m^{-3}, respectively. The authors also reported that saturated hydraulic conductivity measurements indicated that the Bt horizon limited water movement.

The previous crop in all three years was non-fertilized, irrigated corn (*Zea mays* L.). Representative soil samples from 0-15 cm were collected in the spring before planting for routine soil tests (Brown, 1998) (Table 1) and from 0-60 cm soil depth to determine KCl extractable nitrate-N (NO_3-N) and ammonium-N (NH_4-N). Extractable soil NH_4-N in the top 60 cm was 61.4, 28.7, and 73.5 kg ha^{-1} in 2005, 2006, and 2007, respectively. Extractable soil NO_3-N was 25.1, 25.1, and 6.3 kg ha^{-1} in consecutive years. Weather data were collected on station, and thirty year precipitation and temperature normals for Staples, MN were obtained from the National Weather Service for comparison (MCWG, 2007).

Table 1. Soil properties before spring planting at Staples, MN.

	0-15 cm			
	pH	Bray-P (mg kg-1)	Organic Matter (%)	K[1] (mg kg-1)
Average	6.5	32.2	2.2	111.0

[1]Extractable

The experimental design for all three years was six replicates of randomized complete blocks with a split plot restriction on randomization. Two tillage treatments were replicated as whole plots: deep tillage was intended to break up the Bt horizon, while conventional shallow tillage was not. Subplots consisted of eight nitrogen (N) treatments in 2005 and ten N treatments in 2006/2007 (Table 2). Subplots were four rows wide and 6 m in length with row spacing of 76 cm.

Table 2. Nitrogen treatments for kidney beans (*Phaseolus vulgaris* L.).

Treatment[1]	N Source	Planting	Emergence	Prebloom Sidedress	Total N Rate
		kg N ha^{-1}			
1	None	0	0	0	0
2	WSPCU	67	0	0	67
3	Urea	67	0	0	67
4	PCU	67	0	0	67
5	Urea	0	34	0	34
6	PCU	0	34	0	34
7	Urea	0	34	35	67
8	PCU	0	67	0	67
9	Urea	0	34	67	101
10	PCU	0	101	0	101

[1]Treatments 2 and 3 were not included in the 2005 study

In the spring before planting, plots were disked, tilled with a chisel plow and then disked again to level the area for sowing. Tillage plots were plowed to approximately 47 cm for deep and 29 cm for shallow tillage, respectively, under each chisel shank. The plow layer in between chisel shanks ranged from 23 – 39 cm for deep and 17 - 29 cm for shallow tillage. Shallow tillage did plow through the top 4 cm of the Bt horizon on average, but only deep tillage broke though the bottom of the dense layer which ended at an approximate depth of 42 cm. The non-inoculated red kidney bean cultivar "Montcalm" was sown on 31 May 2005, 24 May 2006 and 1 June 2007 to achieve an approximate density of 192 x 10^3 plants ha^{-1}. Planter applied starter fertilizer consisted of 37 kg K ha^{-1} and 17 kg S ha^{-1} as 0-0-40-15. Weeds were controlled by hand and with a pre-emergence application of dimethenamid-p and split applications of bentazon post-emergence.

Two sources of N, uncoated urea and a 90-day release polymer coated urea (PCU), were compared across several rates and timing schemes in all three years. In 2006/2007 two additional treatments compared an additional N source, Nutrisphere Nitrogen (NSN; Specialty Fertilizer Products, Belton, MO) and urea to PCU at the same rate at planting. NSN is reported to delay conversion of urea to ammonium and ammonium to nitrate (Balderson et al., 2007) and is coated with a water soluble polymer. It will be referred to as a water-soluble PCU (WSPCU) from this point on. Urea, PCU and WSPCU applied at planting were banded 5 cm to the side and 5 cm below the seed. PCU and urea applied at emergence were broadcast by hand on 16 June 2005, 8 June 2006 and 21 June 2007. Urea applied at prebloom was sidedressed by hand on 29 June 2005, 28 June 2006, and 5 July 2007. Emergence and sidedress N applications were cultivated or irrigated into the soil within one day of application.

Release rate of N from PCU was determined by burying 3 grams of the fertilizer in sealed plastic mesh containers for two different application timings. Two to three replications of 10 bags were buried at planting and emergence to the depth of the fertilizer band. The mesh bags were retrieved periodically throughout the season, placed in a paper bag and air dried. This method was also used to determine N release from WSPCU, but on the first and subsequent sampling dates no fertilizer remained in the mesh bags. For PCU, the fertilizer prills were removed from the mesh containers by hand, separated from the soil and weighed on a scale. The amount of weight loss was assumed to be equivalent to the amount of N released (Wilson, 2008). Percent of N release (%NR) as a function of cumulative soil growing degree days (GDD) and time (days after planting) was determined by regression. GDD was calculated with soil temperatures based on techniques in Zvomuya et al. (2003), with a base value of 5°C, the temperature below which release of N from the PCU is thought to be limited.

Disease severity (DS) and adventitious roots were evaluated to determine the extent of root rot in each study. Adventitious roots often occur in infected plants (Estevez de Jensen et al., 2002). Nodules were also rated to determine the effect of N treatments on nodulation. In 2005, all ratings were determined during pod-fill in mid-August, while in 2006 and 2007 ratings were estimated when approximately 50% of plants had flowered in mid-July. Five plants from one of the center 2 rows outside of the harvest area were pulled by hand and evaluated. Rating methods are described in Table 3. DS ratings were based on a 1-9 scale in all three years (Estevez de Jensen, 2000), but ratings in 2006 and 2007 had more resolution compared with 2005. Adventitious roots and nodule ratings were based on ranges found in the field for each particular study.

Beans were harvested on 16 September 2005, 29 August 2006 and 7 September 2007. Plants were pulled by hand from the center 3 m of the center two rows in each plot and threshed in a combine to separate beans from plant material. Harvested dry beans were dried to 0% moisture and then weighed for final yield.

A simple economic analysis was conducted to compare net monetary returns of each N and tillage treatment. Dry bean prices were set at \$1.24 kg^{-1}. The cost for deep tillage was \$69 ha^{-1} while shallow tillage was approximately \$40 ha^{-1} (Dale

Schock, personal communication, 2008). Soluble urea was priced at \$1.34 per kg N, PCU at \$1.54 kg^{-1} N, and WSPCU at \$1.52 kg^{-1} N. Application costs were considered \$0 ha^{-1} when fertilizer was applied at planting, since it is applied simultaneously with starter fertilizer. Fertilizer application at sidedress was estimated to be \$17 ha^{-1} per application (Edwards and Smith, 2008). Split sidedressed applications cost double this amount. Net monetary return was calculated based on gross value of the bean crop minus the cost of fertilizer, application and tillage.

Table 3. Methods for rating disease severity, nodules and adventitious roots by year.

2005 Methods	
Disease Ratings	
1	Little to no root rot
3	Visible infection
5	Moving into vascular system
7	Vascular system affected, taproot in tact
9	Complete death of taproot.
Nodule Ratings	
0	No nodules
1	Presence of very few (0-5) small nodules
2	Small number (5-15) of nodules
3	Greater number (15-25) of nodules
4	Highest amount of nodules on plants observed in field (30-40). Also reflected viable live nodulation.
Adventitious roots	
0	No adventitious roots
1	Indicates adventitious (hydroponic) roots.
2006/2007 Methods	
Disease Ratings	
0	No root rot
1	No root rot to Little To Visible
2	Little To Visible infection
3	Visible infection
4	Visible infection to Moving into vascular system
5	Moving into vascular system
6	Moving into vascular system to Vascular system affected, taproot in tact
7	Vascular system affected, taproot in tact
8	Vascular system affected, taproot in tact to Complete death of taproot.
9	Complete death of taproot.
Nodule Ratings	
0	No nodules
1	Presence of very few (0-15) small nodules
2	Small number (15-30) of nodules
3	Greater number (30-45) of nodules
4	Highest amount of nodules on plants observed in field (>45). Also reflected viable live nodulation.
Adventitious roots	
1	0-5 adventitious roots
2	5-15 adventitious roots
3	>15 adventitious roots.

Data from the study were analyzed using PROC MIXED (SAS Institute Inc., 2004) with replications as random variables. Values less than a p-value of 0.10 were considered significant. The 2005 data were analyzed separately, due to the difference in N treatments from the other years. The 2006 and 2007 data were combined and years were also considered random effects. Treatment means were compared using least-square means and contrast statements (SAS Institute Inc., 2004). As described by Littell et al. (2006), differences among treatments within years (the year by treatment interaction), were assessed by year-specific inference using best linear unbiased predictors (BLUPs). For the PCU release rate study and yield data, regression models were fit for each N timing treatment or N source treatment, respectively, and analyzed using PROC MIXED, while final regression equations were estimated with PROC REG (SAS Institute Inc., 2004). Correlations between variables were measured using PROC CORR (SAS Institute Inc., 2004). Spearman correlation coefficients were used if one or more variables were rank data, otherwise Pearson correlation coefficients were used.

RESULTS AND DISCUSSION

Weather

Mean temperature and rainfall for the 2005 through 2007 growing seasons (June through August) and following fall months are compared with 30 year averages for Staples, MN in Table 4. While all three years were warmer than average, 2005 was wetter and 2006 and 2007 were drier than normal. Precipitation totals for the main growing season (June - August) were 29.7, 18.2, and 9.6 cm for consecutive years. The surplus of 1.8 cm of rain in 2006 was increased by rainfall in September and October to a surplus of 4.6 cm. Above average precipitation in September and October of 2006 and 2007 decreased rain deficits of 9.7 and 18.3 cm, respectively, to 8.9 and 7.2 cm, respectively. Supplementary irrigation varied over years (Table 4), but in addition to precipitation, dry beans in 2005 received more water than in 2006 while the crop in 2007 received the lowest amount of water due to a severe drought that limited water supply.

Table 4. Average monthly rainfall and precipitation compared to 30-year averages for Staples, MN.

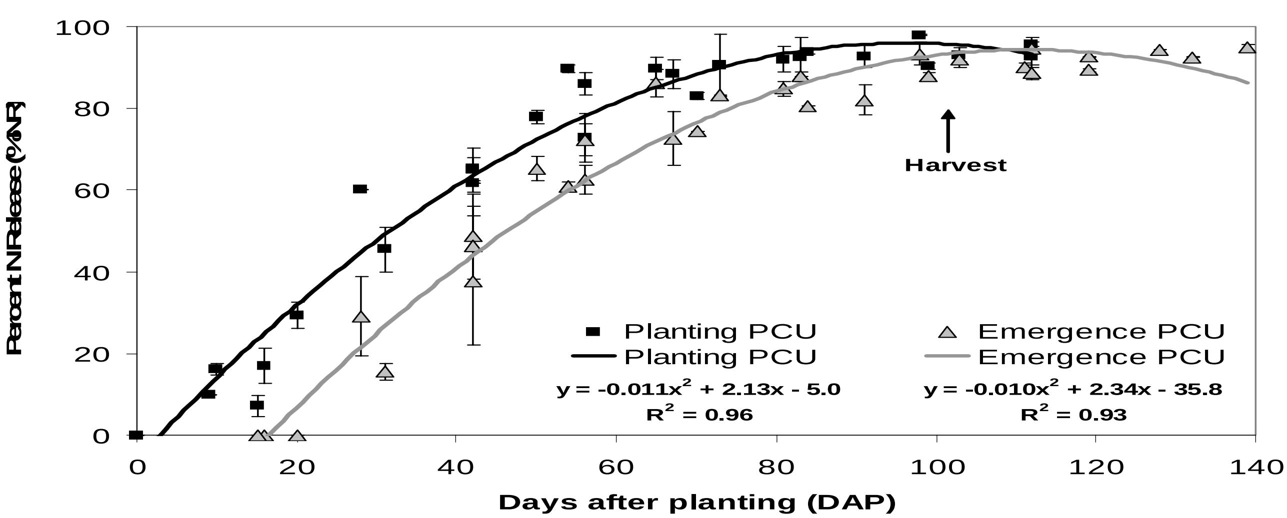
Month	Rainfall				Temperature			
	2005	2006	2007	30-Year Mean[1]	2005	2006	2007	30-Year Mean[1]
	cm				°C			
June	14.2	6.4	4.7	10.8	19.4	18.4	19.4	17.4
July	3.6	4.6	2.9	9.0	21.3	22.6	21.3	19.8
August	11.9	7.2	2.0	8.0	18.5	19.5	18.4	18.8
September	9.1	9.5	14.0	6.6	15.6	12.8	14.4	13.2
October	6.8	4.5	10.2	6.6	7.9	5.1	8.6	6.5
Irrigation	11.7	21.4	27.5					

[1]Average for the 30 year period from 1971-2000.

Nitrogen Release Rate from PCU

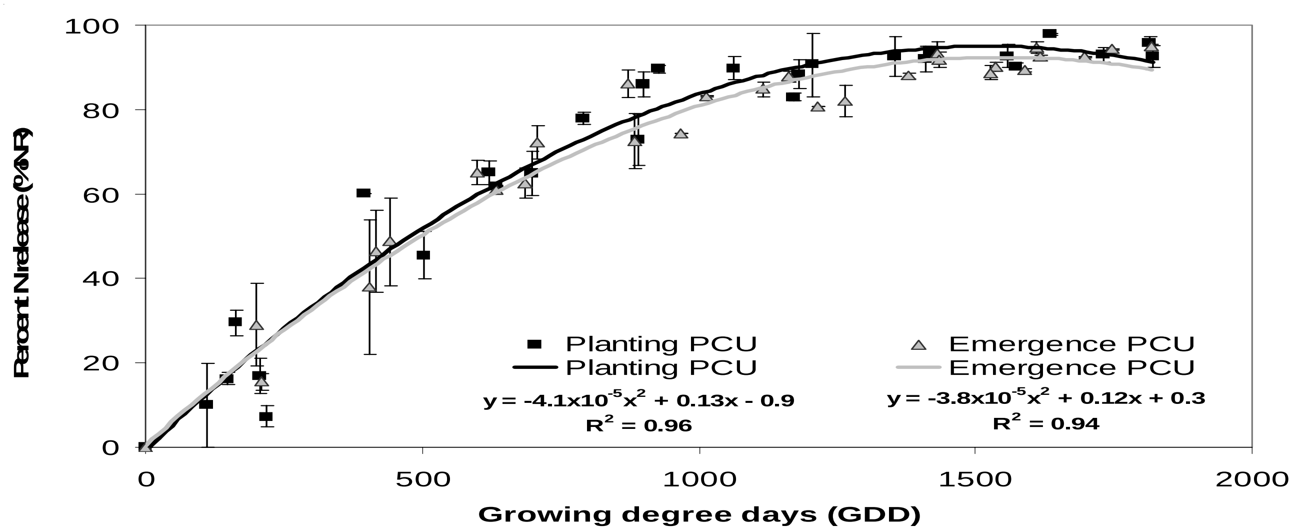
In order to compare N release of PCU at different application times (planting and emergence), equations were used to model release rate. Percent of N release (%NR) was a quadratic function of days after planting (DAP). No differences in regression slopes were found between years for each treatment ($p>0.10$) so one quadratic line is used to describe each timing of application treatment (Figure 1). The intercepts were significantly different between the two treatments due to the difference in application timing. Emergence PCU was typically applied between 15 and 20 DAP during this study. Slopes were not significantly different, indicating that PCU had the same release pattern regardless of application timing. According to the equations, planting and emergence PCU had released approximately 95% and 93% by the average harvesting date (101 DAP), respectively. Total N accumulation for unfertilized dry bean was reported to increase at the highest rate between approximately 45 and 60 DAP (Kimura et al., 2004). Planting PCU had released approximately 60% of the total N supply by 45 DAP, while emergence PCU had only released about 45%. This suggests that emergence application of PCU may be delayed too long for maximum uptake by dry bean, assuming that dry beans accumulate N similarly with or without N fertilizer applications.

Figure 1. Percent of N release (%NR) from a polymer coated urea (PCU) placed at the fertilizer band depth as a function of the number of days of planting (DAP) averaged over three growing seasons.



The release rate of N from PCU is mainly determined by soil temperature when soil moisture is not limiting (Salman et al., 1989; Gandeza and Shoji, 1991). To further explore the relationship between soil temperature and N release, PCU release was expressed as a function of cumulative soil growing degree days (GDD) at the fertilizer band depth. The %NR was determined to be a quadratic function of GDD, agreeing with the model chosen in Zvomuya et al. (2003). One equation was used to describe each treatment when no differences in regression slopes were found between years ($p>0.10$) (Figure 2). The intercepts and slopes for each N timing treatment were not significantly different, suggesting that PCU requires a specific number of GDD to release N, regardless of the number of days needed to accumulate them. This also indicates that the amount of N released from PCU can be predicted if GDD is known. Under the conditions of this study, over 90% of N had been released by 1300 GDD. In each year, beans were harvested at approximately 1650 GDD.

Figure 2. Percent of N release (%NR) from two different application timings of polymer coated urea (PCU) placed at fertilizer band depth as a function of cumulative soil growing degree days (GDD, base of 5°C) after fertilizer application.



Disease Severity and Adventitious Roots

There were no statistically significant findings with disease severity (DS) ratings over the course of this study. In 2005, the average disease rating was 6.6, which is equivalent to the vascular system being affected, but the tap root is still in tact. The disease ratings in 2006 and 2007 were 5.3 and 5.1, respectively, which indicate that root rot was moving into the vascular system. It is not surprising that DS ratings were relatively high in the field trials, due to the previous history of root rot. Differences in DS due to tillage and N treatment were not found. These results agree with the conclusions of Burke et al. (1972) where deep tillage before seedbed preparation failed to affect DS. However, deep tillage after seedbed preparation to break up the compacted plow layer did significantly reduce crop damage from fusarium root rot. Other studies have found varying results of tillage on DS. Estevez de Jensen et al. (2004) found that DS was not affected by moldboard plowing when compared with minimal tillage in a soil similar to the present study. It is unlikely that moldboard plowing broke up the Bt layer, however. Harveson et al. (2005) reported that zone tillage (a type of strip tillage) significantly reduced DS over no-tillage in a soil with a compacted layer. No-tillage was not tested in the current study, and may need further evaluation.

A rating system for the presence of adventitious roots was also employed to determine the effect of tillage practices and N management on disease. Adventitious roots often form above the initial infection area in order to maintain the function of dying roots (Hagedorn and Inglis, 1986; Meronuck et al., 1993). Adventitious roots were not affected by N treatment in any year. In 2005, tillage depth significantly affected the presence of adventitious roots (Table 5). Deep tillage resulted in a higher rating, indicating that on average adventitious roots were present more often than with shallow tillage. In the same year, adventitious root ratings were not correlated with DS ratings, which suggests other factors affected their growth. Severe root rot will affect adventitious roots over time, and given the high average DS rating (6.6 on a scale of 9) and the later timing of measurements in 2005 (77 DAP compared with approximately 44 DAP in 2006/2007), adventitious root growth may have been affected by disease. Roman-Aviles et al. (2004) found that while root rot symptoms were expressed by 30 DAP, root weights were not affected until approximately 60 DAP.

Table 5. Adventitious root ratings as affected by tillage and year.

	Adventitious Root Ratings	
	2005	2006/2007
Tillage		
Deep	0.3 a	2.2 a
Shallow	0.2 b	2.3 a
Year		
2006	---	2.6 a
2007	---	1.9 b

[1]Means followed by the same letter are not significantly different (p>0.10).

Adventitious roots were not significantly affected by tillage in 2006 and 2007, but years were significantly different (Table 5). In 2006, the average plant contained 5-15 adventitious roots, while the average per plant in 2007 ranged from 0-5. These values are slightly lower than those reported in Michigan, where the variety Montcalm grew 15 adventitious roots on average under field conditions (Roman-Aviles et al., 2004).

Adventitious root ratings were inversely correlated with DS ratings in 2006/2007, although variation was high (rho = -0.13, $p<0.05$). Roman-Aviles et al. (2004) also found a negative correlation between adventitious roots and DS, but the study included many varieties with varying levels of susceptibility to root rot. They also found that Montcalm kidney beans had fewer adventitious roots on average compared with more resistant varieties. This suggests that Montcalm (a variety that is highly susceptible to root rot) is less adapted to dealing with root rot via adventitious roots, which may explain the high variability found in our study.

Drought stress in 2006 and 2007 may have affected adventitious root development, regardless of DS. The initiation of adventitious roots was inhibited at a relative humidity of 93% or less in water stressed white clover in a study by Stevenson and Laidlaw (1985). Manschadi et al. (1998) found that root densities of faba bean (*Vicia faba* L.) in upper soil levels were much lower under water stress compared with those of well watered plants. Both 2006 and 2007 had below normal precipitation levels, but the rain deficit in 2007 was more pronounced. The drought conditions in both years also limited irrigation water supplies, especially in 2007. This may explain the low adventitious root ratings compared with other studies and the significant difference between years.

Nodule Ratings

Nodule ratings in 2005 were significantly affected by N treatment (Table 6). In 2005, all N treatments were not significantly different than the control, except the highest rate of PCU (101 kg N ha^{-1}), which produced significantly lower nodule ratings. In the 2006/2007 analysis, the addition of N did not significantly affect nodulation. Moisture stress may adversely affect nodule numbers and size, especially at important growth stages (Sprent, 1976; Peña-Cabriales and Castellanos, 1993), and drought conditions due to inadequate water supply for irrigation in 2006 and 2007 may have limited nodulation.

Table 6. Nodule ratings as affected by N source, rate and timing.

Treatment	N	N	Timing	Nodule Ratings[2]	
#	Source	Rate	(P,E,S)[1]	2005[3]	2006/2007
1	None	0	0,0,0	0.8 a b	1.8 a
2	WSPCU	67	67,0,0	---	1.3 a
3	Urea	67	67,0,0	---	1.4 a
4	PCU	67	67,0,0	0.7 b c	1.3 a
5	Urea	34	0,34,0	1.2 a	1.7 a
6	PCU	34	0,34,0	1.0 a b	1.9 a
7	Urea	67	0,34,33	0.8 a b	1.5 a
8	PCU	67	0,67,0	0.6 b c	1.7 a
9	Urea	101	0,34,67	0.8 a b	1.6 a
10	PCU	101	0,101,0	0.3 c	1.8 a

[1]P,E,S = applied at planting, emergence and pre-bloom sidedress, respectively
[2]Nodule ratings methods differ between 2005 and 2006/2007
[3]2005 did not include treatments 2 and 3 in the experimental design
[4]Means with the same letter are not significantly different ($p>0.10$).

The addition of N to dry bean is reported to decrease N_2 fixation and nodulation (both in nodule mass and number present per plant) (Graham, 1981; Da Silva et al., 1993; Leidi and Rodriguez-Navarro, 2000). This study supports these findings to some degree, since nodule ratings were reduced by some N treatments, especially at the higher N rates.

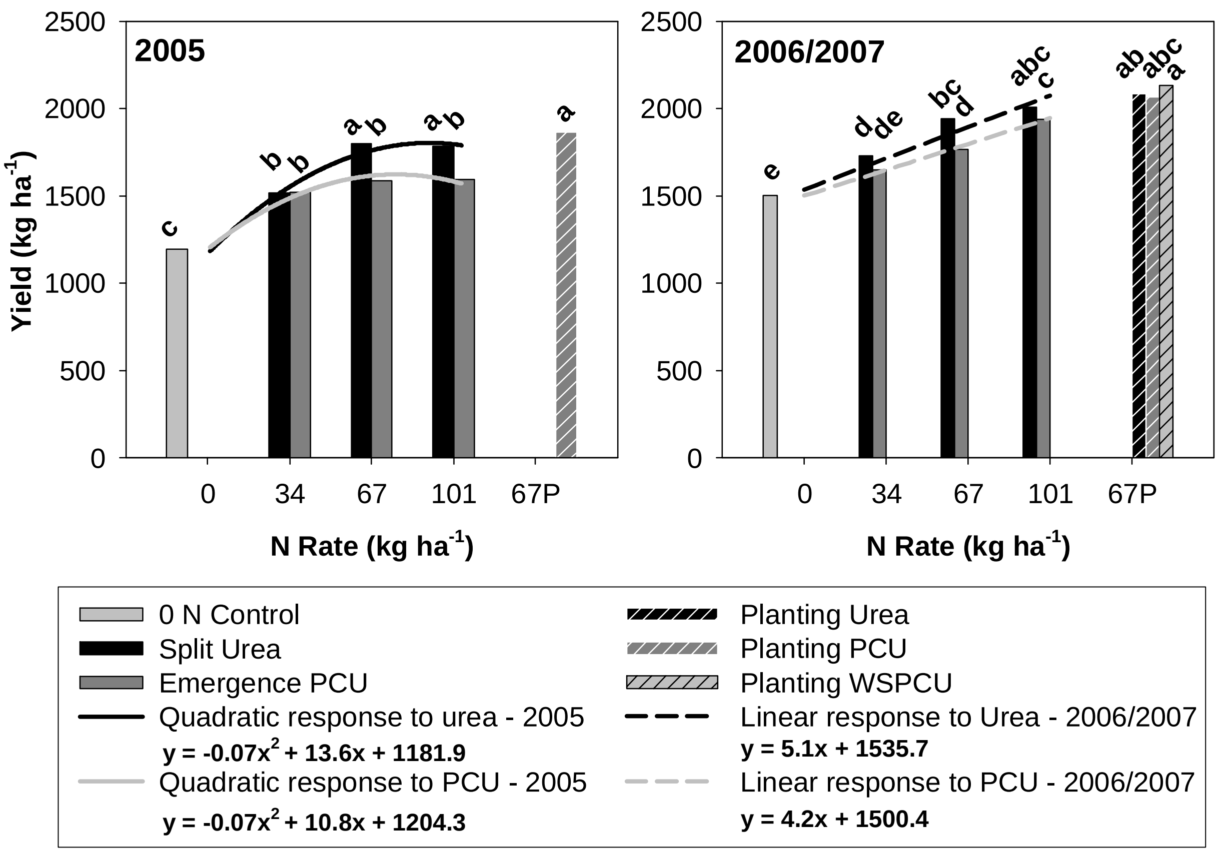
Bean Yields

In 2005, N treatment significantly affected dry bean yields although tillage treatments did not. The addition of N significantly increased yields over the 0 N control, and yield response was a quadratic function of N rate (Figure 3). At the low N rate (30 kg N ha^{-1}), there was no yield difference between N sources, but split urea at 67 and 101 kg N ha^{-1} resulted in significantly higher yields compared with emergence PCU. Bean yields with planting PCU were similar to split urea at the equivalent rate, however.

With N applications at emergence or later, bean yield was a quadratic function of N rate. Slopes and intercepts of the quadratic functions were not significantly different between emergence PCU and split urea, which suggests that yields responded similarly to N source. Since yield responses were a quadratic function, the N rate that would have produced the highest yield can be obtained for 2005. The optimum N rates as calculated from the quadratic equations were 92 and 78 kg N ha^{-1} for split urea and emergence PCU, respectively. Although the two values vary between N sources, the quadratic lines were not significantly different and therefore optimum N rates cannot be assumed to be different either.

Dry bean yields in 2005 were lower when compared with yields in 2006 and 2007, most likely due to excessive moisture conditions early in the season. In 2006 and 2007, N treatments significantly affected dry bean yields. The addition of N significantly increased yields over the 0 N control, except at the lowest N rate (34 kg N ha^{-1}) of emergence PCU (Figure 3). Yield response was a linear function of urea and PCU N rate. This suggests that an optimum rate was not reached within the parameters of this study or that additional N may have increased yields further. Slopes and intercepts for each N source were not significantly different. Split urea generally resulted in higher yields compared with emergence PCU, although differences were only significant at the 67 kg ha^{-1} N rate. N applied at planting resulted in the highest yields, but there were no differences between N sources. Planting WSPCU resulted in significantly higher yields than all other emergence applied N treatments except split urea applied at 101 kg N ha^{-1}. Yields with planting PCU were similar to yields with emergence applied PCU and split urea at the highest N rate (101 kg N ha^{-1}) and split urea at 67 kg N ha^{-1}, but were significantly higher than yields with all other emergence PCU applications. In contrast to the current study, Henson and Bliss (1991) found that applying soluble N at planting generally reduced yields due to nodule inhibition compared with later N applications. In the present study, bean nodule ratings were not affected by N timing treatments, although moisture stress may have limited their growth.

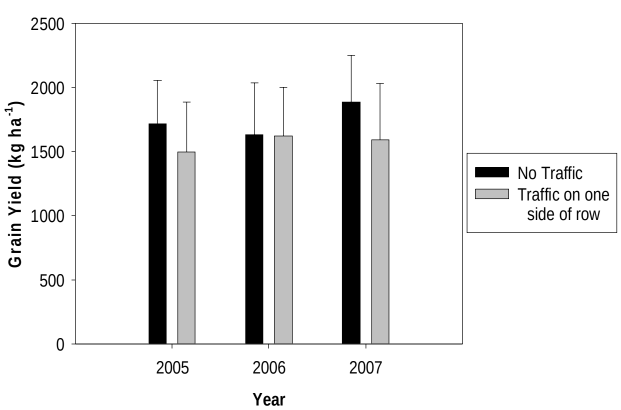
Figure 3. Dry bean grain yield as affected by N source, rate and timing. Yield response to N rate (for N applied at emergence or later is also presented. Bars with the same letter (2005 and 2006/2007 are considered separately) are not significantly different (p>0.10).



Several studies have concluded that tillage practices affected dry bean yields. Estevez de Jensen et al. (2004) reported increased grain yields with moldboard plowing compared with disking on a soil similar to the one in the present study. A deep tillage method was not used to break up the Bt horizon, however, such as in the current study. Harveson et al. (2005) found that zone tillage to break up a compacted layer significantly increased bean yields over no-tillage. Burke et al. (1972) found that yields were not affected by subsoiling before seedbed preparation, but were significantly increased with subsoiling between the rows after seedbed preparation. In the current study, yields were not significantly different between tillage treatments in all three years, which suggests preparation of the seedbed may have resulted in re-compaction even though the Bt layer was broken up. Further research needs to be conducted to determine optimal tillage timing in combination with field preparation.

Further examination of the yield data found that another factor may have affected grain yield. Yields were determined separately from each harvest row in order to determine if there was an effect of wheel traffic on grain production. Of the two center rows of beans used for harvest, one row had wheel traffic on one side while there was no traffic adjacent to the other harvest row. The tractor used for planting had single wheels that were approximately 46 cm in width, which left approximately 15 cm between the wheel and the row. While the experimental design of this study did not allow for statistical analysis, general trends were found. Averaged over tillage and N treatments in each year, there tended to be a decrease in grain yield when the row was next to wheel traffic compared with the row without any traffic nearby (Figure 4). The difference in yield was more pronounced in 2005 and 2007 than in 2006 and may be due to soil moisture conditions. Wet soils are more susceptible to increased compaction than dry soils (DeJong-Hughes et al., 2001), and there was little precipitation in the first half of the growing season in 2006. Wet field conditions occurred during post-emergence field operations in 2005 and at planting in 2007, respectively.

Figure 4. Kidney bean yields averaged over tillage and N treatments as affected by wheel traffic in three years.



Averaged over three years, there was generally a 9% yield loss due to traffic. With an 8 row planter, approximately 50% of the yield will be reduced since 4 rows are adjacent to wheel traffic. To reduce the proportion of the yield affected, a larger planter should be used. Many have reported that compaction of a sandy soil with wheel traffic significantly reduced yields of various crops (Mamman and Ohu, 1997; Dauda and Samari, 2002; Nevens and Reheul, 2003). These studies have typically compacted entire plots with wheel traffic which is not practiced in traditional crop production. The current study, however, found that there may be an effect of wheel traffic on kidney bean yields as it applies to conventional kidney bean production practices.

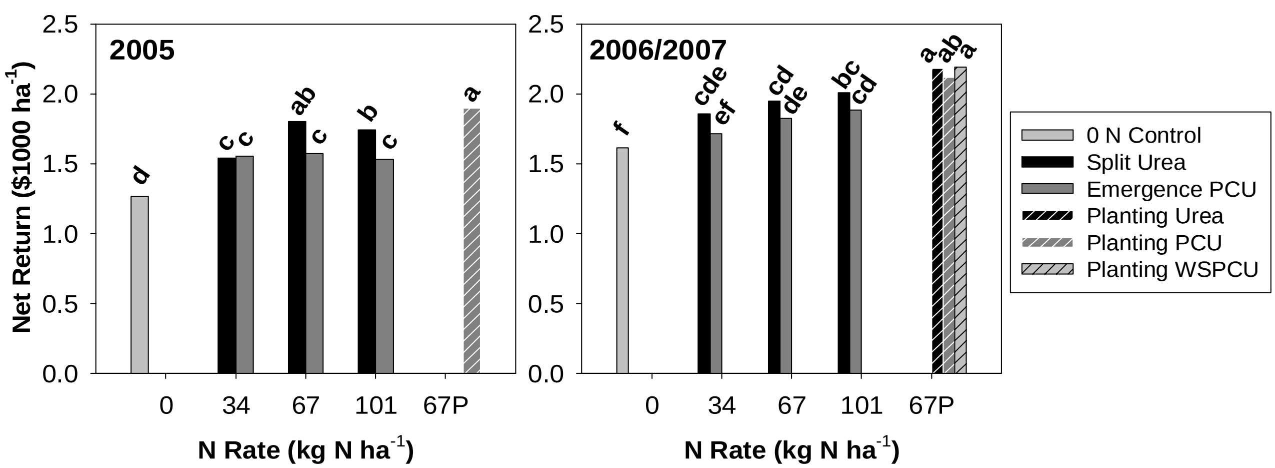
Economic Analysis

An economic analysis of the current study was conducted to show net monetary returns based on fertilizer prices, application costs, tillage costs and dry bean yields. Net returns in 2005 (\$1263 – \$1896 ha^{-1}) were generally lower compared with 2006 and 2007 (\$1614 – \$2189 ha^{-1}), mainly due to lower yields. In 2005 and 2006/2007, N treatments significantly affected net monetary returns for bean production (Figure 5). In 2005, the addition of N significantly increased returns over the zero N control. Planting PCU and split urea at equivalent rates resulted in the highest net returns, although split urea at 67 kg N ha^{-1} was not significantly different from split urea at 101 kg N ha^{-1}. Increasing N rate with emergence PCU did not result in an increase in net return. Net returns with split applied urea significantly increased between 34 and 67 kg N ha^{-1} and then remained statistically the same at 101 kg N ha^{-1}. At the lowest N rate, there were no differences in returns between N sources, but at 67 and 101 kg N ha^{-1}, split urea resulted in a significantly higher net return than emergence PCU.

In 2006 and 2007, the addition of N significantly increased net returns over the zero N control, except at the lowest rate of emergence PCU. Planting applied N significantly increased monetary returns over all emergence or later applied N, and all planting N sources resulted in similar returns. In general, net returns were increased as N rate applied at emergence increased, although split urea treatments did not result in significantly different returns. The highest rate of emergence PCU (101 kg N ha^{-1}) resulted in a significantly higher net return compared with the lowest rate (34 kg N ha^{-1}), while 67 kg N ha^{-1} was similar to both. Split urea resulted in higher net returns than emergence PCU, although these differences were not significant.

Overall, emergence applied PCU resulted in reduced net returns in a wet year compared with uncoated urea, but planting applied PCU was comparable at equivalent rates. Under dry conditions, emergence PCU and split urea resulted in similar returns, but the highest returns were with planting N applications, regardless of N source. Tillage depth did not affect net returns in any year, due to the lack of a yield response and the low cost of tillage compared with net returns.

Figure 5. Net monetary returns as a function of N source, rate and timing. Bars with the same letters (2005 is separate from 2006/2007) are not significantly different (p>0.10).



CONCLUSIONS

This study was conducted to examine different tillage techniques and polymer coated ureas on irrigated dry bean production in Minnesota. In general, tillage treatments did not affect disease severity ratings, nodulation, kidney bean yields, or net monetary returns. The current study conducted tillage before seedbed preparation however, and others have reported that only tillage after preparation of the seedbed resulted in yield differences (Burke et al., 1972). Future research should focus on timing of tillage to find the optimal treatment for bean production.

Emergence applied PCU resulted in lower grain yields compared with split applications of urea at emergence and prebloom. The N release study of PCU suggested that emergence applied PCU had released less than 50% of N when maximum plant N accumulation began. When applied at planting, PCU resulted in similar yields and net returns as split applied and planting urea at equivalent rates over three years. Based on these results, we conclude that emergence applications of PCU may release N too late for the period of maximum N uptake in dry beans, but planting applications of PCU have shown promising results. WSPCU applied at planting also resulted in similar yields and net returns as planting applied urea over 2 years. Further research should focus on finding the optimal N rate for planting applied PCU or WSPCU or test other PCU formulations that release N more quickly.

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Kidney bean (*Phaseolus vulgaris* L.) production on an irrigated, coarse-textured soil in response to polymer coated urea and tillage: II. Plant N accumulation, nitrate leaching and residual inorganic soil N

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ABSTRACT

Kidney bean (*Phaseolus vulgaris* L.) production in Minnesota is inherently at risk for nitrate (NO_3) leaching since the crop is typically grown on irrigated coarse-textured soils. These soils contain a dense Bt layer, which growers feel must be broken up through deep plowing to reduce severity of root rot. This study was conducted to determine the effects of polymer coated urea (PCU, Agrium U.S. Inc. and WSPCU, Specialty Fertilizer Products) and tillage depth on water percolation, nitrate leaching, and plant nitrogen (N) uptake. In a split plot design, deep and shallow tillage (plow depths of 47 and 29 cm, respectively) were whole plots while N treatments were subplots. Three rates of emergence applied PCU were compared with equivalent rates of urea split applied at emergence and prebloom. Along with a 0 N control, additional treatments included one rate of each N source, including WSPCU, applied at planting. Differences between tillage treatments were not found except as interactions with N treatment. In dry years, emergence applied PCU resulted in reduced grain N uptake and more cumulative NO_3 leaching than split applied urea. In a wet year, however, emergence applied PCU resulted in similar plant N uptake and significantly less NO_3 leaching that split applied urea. Planting applied PCU resulted in similar plant N uptake and generally less NO_3 leaching compared with split applied and planting urea, regardless of leaching conditions. In dry years, planting applied WSPCU resulted in similar grain N uptake and NO_3 leaching as planting applied urea and PCU.

Keywords: kidney bean, polymer coated urea, nitrogen rate, tillage, nitrate leaching and plant nitrogen uptake.

INTRODUCTION

Minnesota is one of the top five dry bean producing states in the U.S. and is ranked first in production of dark red kidney beans (*Phaseolus vulgaris* L.) (NASS, 2004). Approximately 59,000 hectares of dry beans were harvested in the state in 2007 (NASS, 2007). Dry beans are typically grown in well drained soils and generally require 2.5-3.8 cm of water every 4-5 days (Egel et al., 2008), which is often supplied by irrigation during peak evapotranspiration demand. In Central Minnesota, dry bean production occurs on irrigated coarse textured soils that have a well defined Bt horizon with increased bulk density and reduced hydraulic conductivity. This area has a past history of severe root rot (Estevez de Jensen et al., 2004), which may be aggravated by the presence of the Bt horizon that confines the pathogen and plant roots to the plow layer (Burke et al., 1972). It has been shown that breaking up a restrictive layer through tillage can increase yields

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and reduce disease severity (Burke et al., 1972; Harveson et al., 2005), but this practice has not been extensively studied in Minnesota.

Current cultural practices for dry bean production in Minnesota are inherently at an increased risk for nitrate (NO_3) leaching to groundwater. Although fertilizer N recovery is often low for dry beans (<50%) (Rennie and Kemp, 1983; Tsai et al., 1993; Kipe-Nolt and Giller, 1993), current recommendations on coarse-textured soils often call for split N fertilizer applications. This combined with additional soil N supplied by biological N fixation and unpredictable rain events increases the potential for NO_3 leaching to groundwater. Breaking up the restrictive Bt layer that is often present in the coarse textured soils of bean production regions may enhance water percolation beyond the root zone and further exacerbate the NO_3 leaching problem.

Controlled release fertilizers (CRF) are one option to reduce NO_3 leaching. CRFs attempt to match the release of N to plant uptake unlike soluble N sources which allow most N to be available to the plant in a short period of time. Reports have shown that a certain type of CRF, called polymer coated urea (PCU), increased N uptake by the plant and reduced NO_3 leaching. Zvomuya et al. (2003) reported that polymer coated urea (PCU) applied to potato significantly reduced NO_3 leaching and increased potato N uptake over split applications of urea in Minnesota. In a pot experiment, N uptake of citrus rootstock seedlings was greater with PCU than urea (Dou and Alva, 1998).

Producers have been hesitant to use PCU due to high prices (Trenkel, 1997; Zvomuya and Rosen, 2001) even though results have been promising. Recent technological advances have provided a new brand of PCU to the market that is competitively priced with other N fertilizers. The use of this PCU, called Environmentally Smart Nitrogen (ESN, Agrium U.S. Inc), resulted in reduced NO_3 leaching in potato compared with untreated N sources (Wilson, 2008). The effect of PCU on NO_3 leaching in dry bean production has not been previously studied.

The overall objectives of this study were to compare several variables on dry bean N accumulation, NO_3 leaching and residual inorganic soil N, including: 1) deep tillage versus shallow tillage (breaking up the Bt horizon versus not), 2) PCU versus untreated N sources at varying N rates and timing of application, and 3) interactions between tillage depth and N treatments.

METHODS AND MATERIALS

Field experiments were conducted over three years during 2005-2007 at the Central Lakes College Agricultural Irrigation Experiment Station near Staples, MN. The soil present at this location is a Verndale sandy loam (frigid Typic Argiudoll) with a 17 cm thick Bt horizon beginning at approximately 25 cm below the top of the soil. This area has a history of severe root rot and Estevez de Jensen et al. (2004) reported that the soil is naturally infested with *Fusarium oxysporum*, *F. solani* f. sp. *phaseoli*, and *Rhizoctonia solani* AG-4.

A detailed explanation of field practices and conditions for this study is reported in Wilson (2008). In summary, the previous crop in all three years was unfertilized, irrigated corn (*Zea mays* L.). Representative soil samples from 0-60 cm were collected in the spring before planting to determine KCl extractable nitrate-N (NO_3-N) and ammonium-N (NH_4-N). Extractable soil NO_3-N in the top 60 cm was 25.1, 25.1, and 6.3 kg ha^{-1} in 2005, 2006, and 2007, respectively. Extractable soil NH_4-N was 61.4, 28.7, and 73.5 kg ha^{-1} in the consecutive years. Weather data were collected on station and thirty year precipitation and temperature normals for Staples, MN were obtained from the National Weather Service for comparison (MCWG, 2007).

A completely randomized block design with 6 replicates was used for all three years, with a split plot restriction on randomization. Two tillage treatments were replicated as whole plots: deep tillage (plowed to approximately 47 cm) was intended to break up the Bt horizon, while conventional shallow tillage (plowed to approximately 29 cm) was not. Subplots consisted of eight nitrogen (N) treatments in 2005 and ten N treatments in 2006/2007 (Table 1). Subplots were four rows wide and 6 m in length with row spacing of 76 cm. The non-inoculated dark red kidney bean cultivar "Montcalm" was sown on 31 May 2005, 24 May 2006 and 1 June 2007 to achieve an approximate density of 192 x 10^3 plants ha^{-1}.

Table 1. Nitrogen treatments applied to kidney beans (*Phaseolus vulgaris* L).

Treatment[1]	N Source	Planting	Emergence	Prebloom Sidedress	Total N Rate
		--------------------------	kg N ha^{-1}	----------------------	
1	None	0	0	0	0
2	WSPCU	67	0	0	67
3	Urea	67	0	0	67
4	PCU	67	0	0	67
5	Urea	0	34	0	34
6	PCU	0	34	0	34
7	Urea	0	34	35	67
8	PCU	0	67	0	67
9	Urea	0	34	67	101
10	PCU	0	101	0	101

[1]Treatments 2 and 3 were not included in 2005 study

Planter applied starter fertilizer was banded and consisted of 37 kg K ha^{-1} and 17 kg S ha^{-1} as 0-0-40-15. Two sources of N, a 90-day release polymer coated urea (PCU) and an uncoated urea were compared across several rates and timing schemes in all three years. In 2006/2007 two additional treatments compared an additional N source, Nutrisphere Nitrogen (NSN; Specialty Fertilizer Products, Belton, MO) and urea to PCU at the same rate at planting. NSN is coated with a soluble polymer that is reported to reduce volatilization and nitrification (Balderson et al., 2007) and will be referred to as a water-soluble PCU (WSPCU). The three N sources applied at planting were banded 5 cm to the side and 5 cm below the seed. PCU and urea applied at emergence were broadcast by hand on 16 June, 8 June and 21 June in the three consecutive years. Urea applied at prebloom was sidedressed by hand on 29 June 2005, 28 June 2006, and 5 July 2007. Emergence and sidedress N applications were cultivated or irrigated into the soil within one day of application.

For measurement of soil-water NO_3 concentration, suction cup samplers with a porous ceramic cup (1 bar high flow, Soil Moisture Equipment, Santa Barbara, CA) were installed 120 cm vertically below the soil surface in each plot according to methods described in Zvomuya et al. (2003). Samplers were installed within one week of planting in four replicates of each treatment. A suction of 40 kPa was applied by hand pump to collect soil water draining through the soil at the depth of installation. A depth of 120 cm was assumed to be sufficiently below the root zone so that NO_3 in the soil water was therefore leached. Soil water samples were collected approximately once a week during the growing season or more often if drainage was suspected to occur, such as after 1 cm or more of rain. Sampling began 2-3 weeks after planting and continued until ground freeze in November. Several samples were also taken after ground thaw during the following spring to determine residual soil-water NO_3, although these were not used in leaching calculations. Samples were kept frozen until analysis and NO_3-N was determined with a Hach DR4000 or DR50000 spectrophotometer (method 10049, Hach, 2005).

Soil moisture measurements were taken in tillage plots with a neutron probe (503DR Hydroprobe, Martinez, CA) in order to estimate stored soil water. One access tube made of galvanized steel electrical tubing was installed in the center of each tillage plot to an approximate depth of 2 m below the top of the soil within one week of planting. Soil moisture measurements were made for the top 120 cm in the soil, with readings taken every 24 cm beginning at 12 cm below the soil surface. Readings were taken once a week or more often if a drainage event was thought to have occurred. When evapotranspiration was low in the fall of each year, the soil water field capacity was determined for each tillage plot. For Verndale sandy loam, the average available water capacity is estimated to be 12.6 cm of water in the upper 120 cm of soil (Aldeen, 1991) but more precise measurements were needed. When antecedent moisture conditions (approximately 9 cm of water in 100 cm of soil) were relatively high preceding a significant rainfall event (> 3.8 cm for this study), field capacity was assumed to have been exceeded. This allowed an estimation of field capacity after drainage occurred for at least 24 hours. For calibration purposes, soil samples were collected during installation of the access tubes and soil water content determined at depths corresponding to the depths at which neutron probe readings were taken in all years. Additionally, calibration equations were determined with methods similar to those in Douglass (1966). Three major horizons of soil (Ap, Bt and Bw horizons) at the study site were excavated, air dried and repacked into 200 liter drums. Measurements taken in dry soil and at saturation (after known amounts of water were added) and at several levels in between were related to soil wetness as determined by time domain reflectometry in order to calibrate the neutron probe for each specific soil horizon.

Daily water percolation at 120 cm below the dry bean crop was determined with the water balance equation as presented in Waddell et al. (2000) and field measurements of soil moisture. The water balance between two consecutive days was calculated as:

$$D = P + I - E - \Delta S \qquad [1]$$

where D was the amount of daily drainage, P was precipitation, I was irrigation water applied, E was evapotranspiration, and “S was the change in soil water storage between two days. The E values were calculated as a product of the potential evapotranspiration (E_o) estimated by a modified Jensen-Haise equation (Killen, 1984) and the crop coefficient (K_c) at a given crop developmental stage. The change in soil water storage was corrected by field measurements of soil moisture when measurements were available. Initial water storage at the beginning of the season and maximum water storage on any particular day was equal to the calculated soil water holding capacity of the 120 cm soil profile. Cumulative water percolation over the growing season was the sum of all percolation events from planting until 30 November of each year.

To determine the daily NO_3-N leached, water percolation was converted to a volume basis, and multiplied by the NO_3-N concentration of the soil water on that particular day. Since soil water samples were not taken on a daily basis, water NO_3-N concentrations between two consecutive sampling dates were linearly interpolated for each day to cover the entire sampling period (June to November). The linear interpolation method may not account for daily fluctuations in NO_3-N concentrations, but possible errors were minimized by sampling at short intervals and by maintaining a continuous vacuum in the suction samplers. Total NO_3 leaching losses over the growing season were the sum of all daily leaching events during the sampling period.

Beans were harvested on 16 September 2005, 29 August 2006 and 7 September 2007. Plants were pulled by hand from the center 3 m of the center two rows in each plot and threshed in a combine to separate beans from plant material. Harvested dry beans were dried at 60°C until 0% moisture and then weighed for final yield. In addition, four plants from each plot were randomly selected for measurement of above ground dry matter and N accumulation. Plants were dried at 60°C, and final weights for dry matter yield were obtained separately for beans and shoots. Beans were ground with a Stein Mill and shoots with a Wiley Mill to pass though a 2 mm screen. Total N in ground samples was determined with a combustion analyzer (Elementar Vario EL) following methods in Horneck and Miller (1998). Nitrogen content of shoots and beans was calculated as the product of dry matter yields and percent N. Total N content was the sum of shoot and bean N contents.

After harvest, a composited five soil core sample to 60 cm depth was collected from each plot to determine the residual soil inorganic N. Soils were air dried, ground, and extracted with 2 *M* KCl. Nitrate-N and NH_4-N in KCl extracts were determined using the diffusion conductivity method (Carlson et al., 1990). Total inorganic N in the soil was the sum of soil NO_3-N and NH_4-N.

Data from the study were analyzed with replicates as a random variable in PROC MIXED (SAS Institute Inc., 2004). The 2005 data were analyzed separately due to differences in N treatments from the other years. Data in 2006 and 2007 were combined and year was treated as a random effect. Treatment means were compared using least-square means and contrast statements (SAS Institute Inc., 2004). Fixed effects and mean separations with a p-value less than 0.10 were considered significant. As described by Littell et al. (2006), differences among treatments within years (the year by treatment interaction), were assessed by year-specific inference using best linear unbiased predictors (BLUPs). Pearson correlation coefficients in PROC CORR were used to test for correlations between variables (SAS Institute Inc., 2004).

RESULTS AND DISCUSSION

Weather and Water Percolation

The deviation of precipitation and temperature from the 30-year averages are in Table 2. Overall, all three years were warmer than on average, but 2005 was wetter and 2006 and 2007 were drier than normal conditions. Precipitation totals for the growing season (June - August) were 29.7, 18.2, and 9.6 cm for 2005, 2006, and 2007, respectively. Supplementary irrigation supplied an additional 11.7, 21.4 and 27.5 cm of water in consecutive years. Total water supply to the crop (precipitation + irrigation) was highest in 2005 and lowest in 2007.

Tillage treatments did not significantly affect cumulative water percolation, but there tended to be differences among years. Water percolation between planting and ground freeze was lower in 2006 than in 2007, and total percolation in 2005 and 2007 was similar (total percolation was 30.4, 21.3 and 30.3 cm in consecutive years). While 2005 and 2007 were comparable in total percolation, water movement over time is mainly influenced by rain patterns and irrigation, which varied greatly over years (Figure 1). In 2005, approximately 25% of the total water percolation occurred between planting and application of emergence fertilizer, while percolation remained relatively unchanged during the same time period in the following years (2007 had an initial leaching event at planting). Approximately 18, 11, and 11 cm of water had percolated from planting to harvest in 2005, 2006, and 2007, respectively. Considerable water losses occurred after harvest in all three years: 40% in 2005, 48% in 2006, and 64% in 2007.

Nitrate Leaching

Nitrate leaching patterns over the growing season were greatly influenced by the rainfall patterns and irrigation of each year. In 2005, approximately 27% of total NO_3 leached occurred between planting and emergence, while 38% occurred after harvest (Figure 2). In 2006, only 2% of total leaching occurred between planting and emergence, while 43% occurred after harvest (Figure 3). In 2007, 8% of leaching occurred between planting and emergence while 68% of

Table 2. Departure of rainfall and temperature over three years from the 30-year averages for Staples, MN.

	Rainfall				Temperature			
	30-Year	Departure from normal			30-Year	Departure from normal		
Month	Mean[1]	2005	2006	2007	Mean[1]	2005	2006	2007
	cm				°C			
May	7.6	0.8	-2.4	3.9	12.7	-0.7	0.8	1.6
June	10.8	3.3	-4.4	-6.2	17.4	2.0	1.0	2.0
July	9.0	-5.4	-4.5	-6.2	19.8	1.4	2.8	1.5
August	8.0	3.9	-0.8	-6.0	18.8	-0.2	0.7	-0.3
September	6.6	2.6	2.9	7.5	13.2	2.4	-0.3	1.3
October	6.6	0.2	-2.1	3.6	6.5	1.5	-1.3	2.2
November	3.7	3.9	-1.9	-3.5	-3.0	2.8	1.7	0.9

[1]Average for the 30 year period from 1971-2000.

total NO_3 leaching occurred post-harvest (Figure 4). Differences between N sources generally began occurring between 15 and 45 days after planting (DAP) in 2005, at 70 DAP in 2006 and not until 108 DAP in 2007. High NO_3 losses post-harvest were not only due to above average rainfall in all 3 years, but also because soil water NO_3 concentrations slowly increased over the season to their peak levels after plant senescence and harvest (data not shown).

Figure 1. Daily precipitation and irrigation over three years during the growing season and the following fall months. Cumulative water percolation below 120 cm soil depth is also presented.

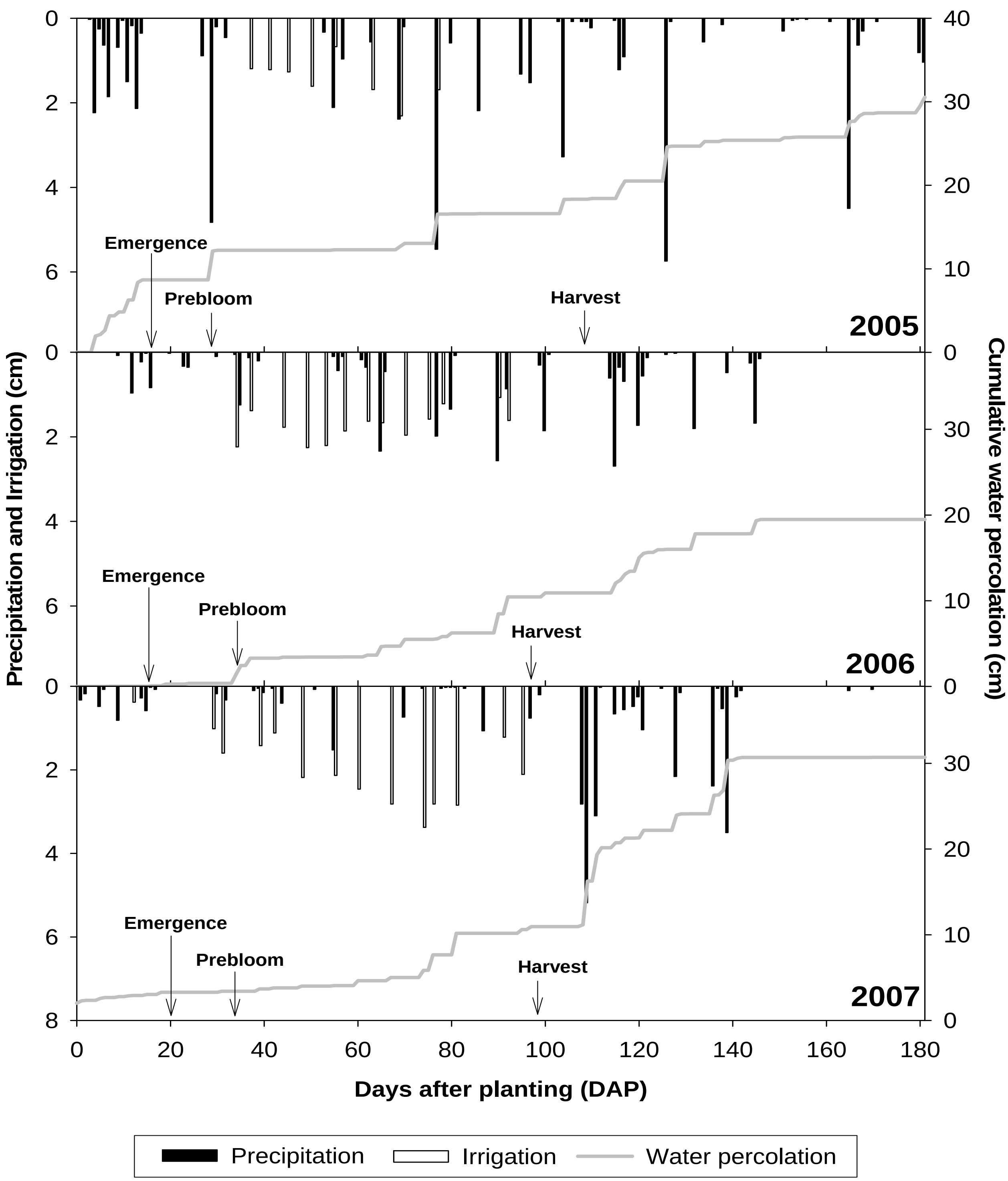


Figure 2. Daily and cumulative nitrate (NO_3) leaching over the 2005 growing season as influenced by N source, rate and timing. Emergence applications of N were either all applied at emergence. (PCU) or split applied at emergence and prebloom (urea).

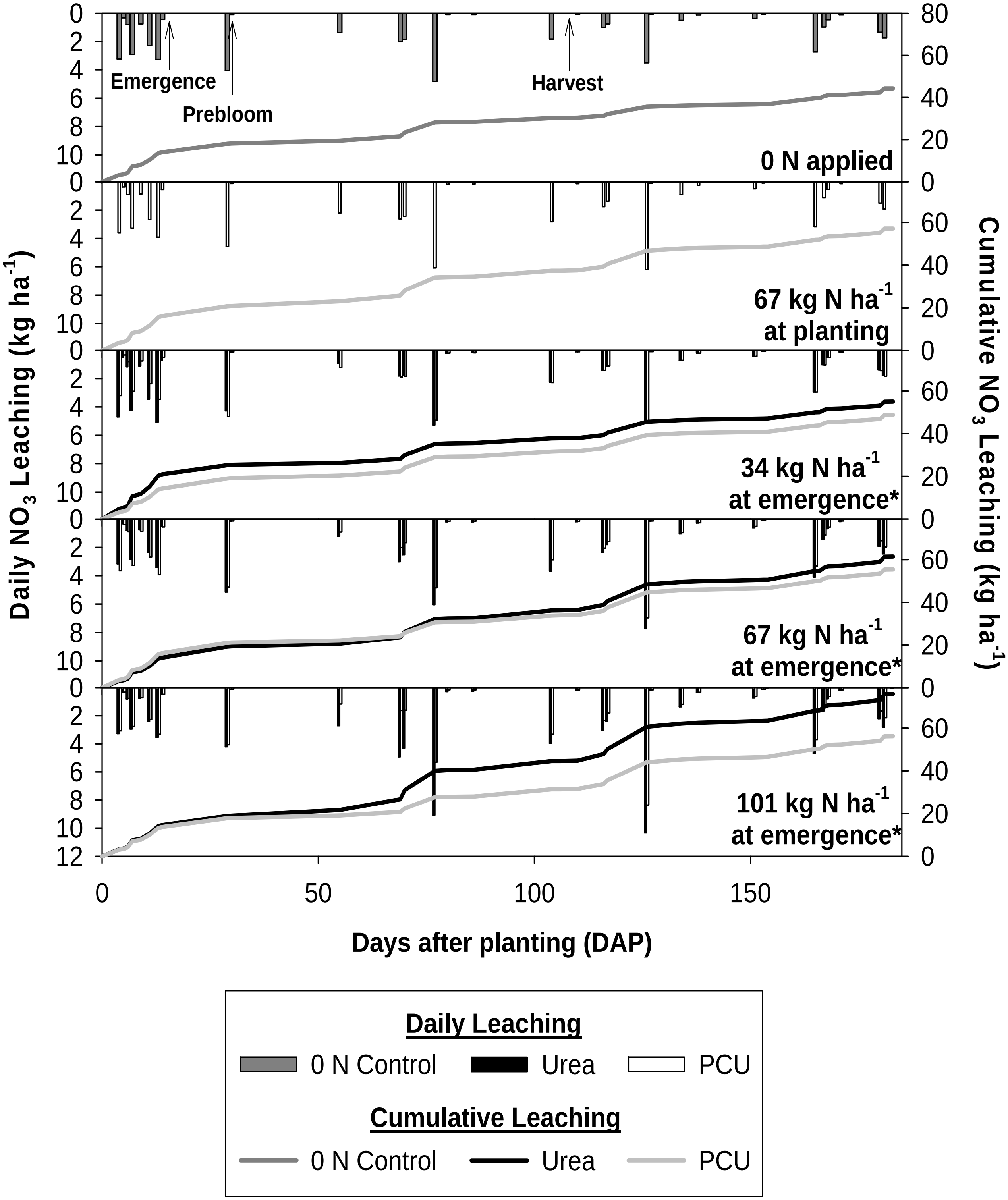


Figure 3. Daily and cumulative nitrate (NO_3) leaching over the 2006 growing season as influenced by N treatment, rate and timing. Emergence applications of N were either all applied at emergence(PCU) or split applied at emergence and prebloom (urea).

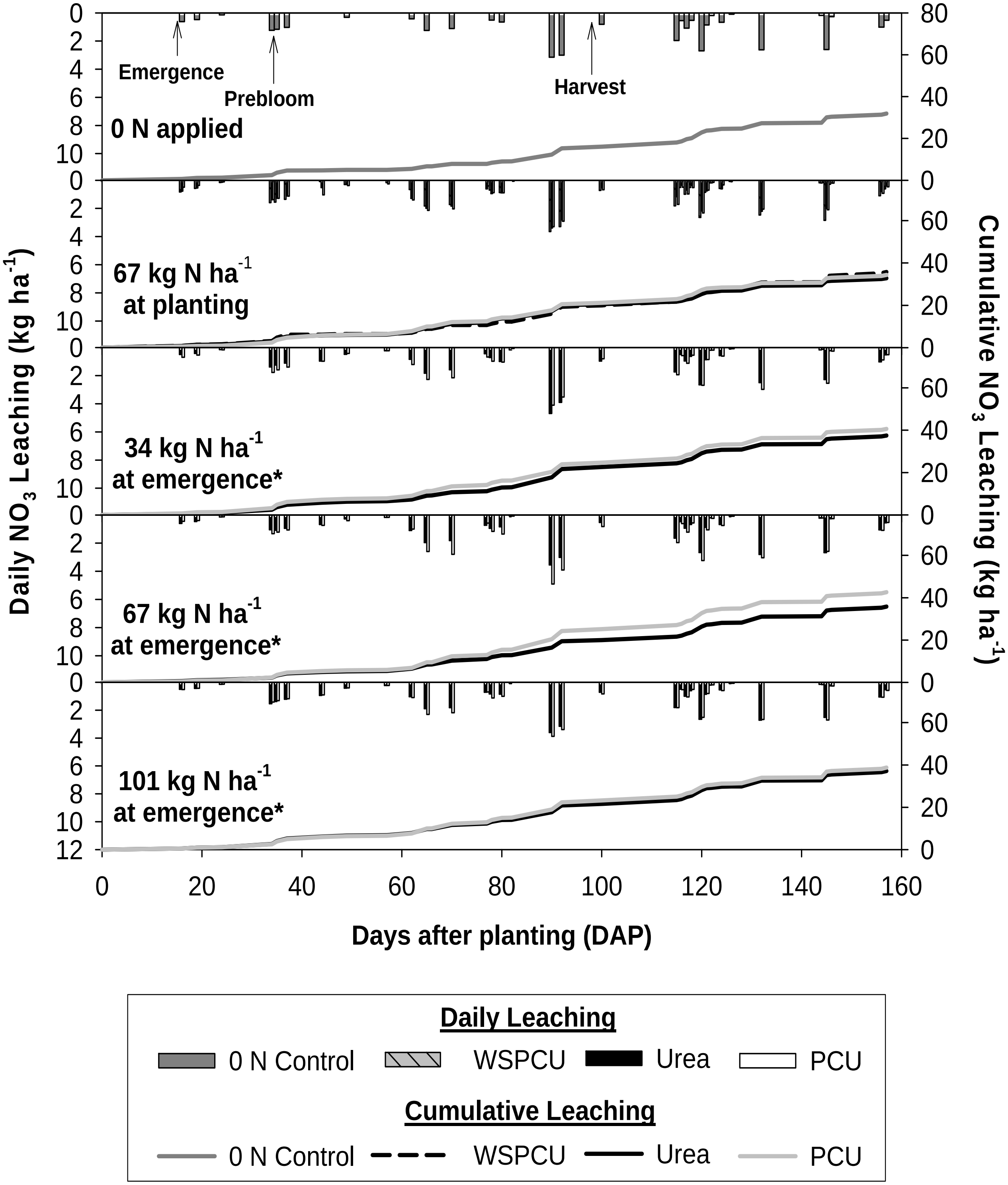
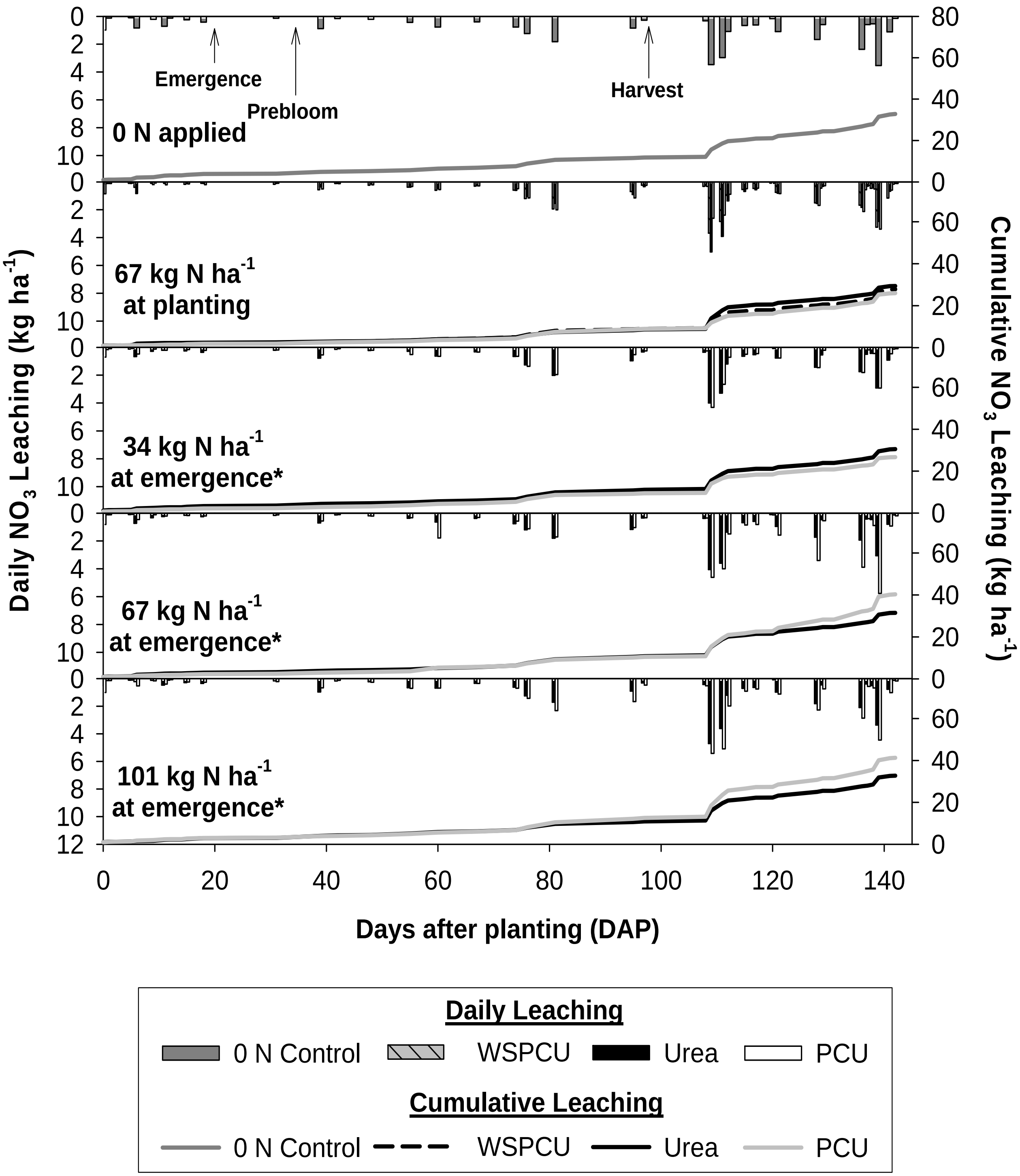
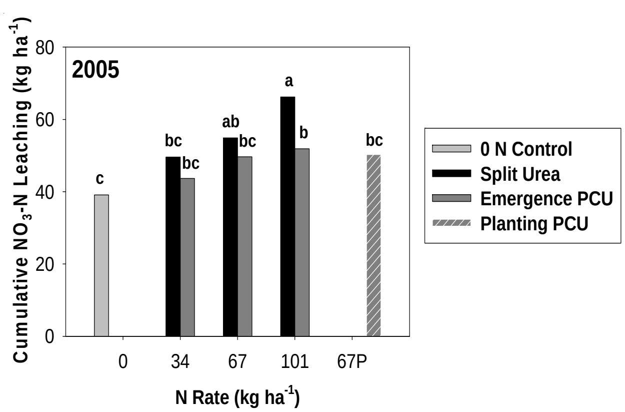


Figure 4. Daily and cumulative nitrate (NO_3) leaching over the 2007 growing season as influenced by N treatment, rate and timing. Emergence applications of N were either all applied at emergence (PCU) or split applied at emergence and prebloom (urea).



Meek et al. (1995) reported that approximately 42 kg N ha^{-1} as NO_3 leached from unfertilized dry beans in Idaho under normal precipitation conditions, which is similar to the NO_3 leached from 0 N control in 2005. Cumulative NO_3 leaching in 2006 and 2007 was generally lower due to low leaching conditions. In 2005, cumulative NO_3 leaching was significantly affected by N treatments, but not by tillage or the tillage by N treatment interaction (Figure 5). In general, an increase in N rate caused numerical increases in NO_3 leaching. However, only urea applied at 67 kg N ha^{-1} and the highest rate of N (101 kg N ha^{-1}) for both urea and PCU resulted in significantly higher NO_3 leaching compared with the 0 N control. N source did not affect NO_3 leaching at lower N rates, but 101 kg N ha^{-1} of PCU resulted in significantly less nitrate leaching than urea at the equivalent rate. Contrast statements were used to compare all N rates of emergence PCU to all rates of split urea in 2005. NO_3 leaching was significantly reduced with emergence PCU compared with split urea.

Figure 5. Cumulative nitrate (NO_3) leaching over the 2005 growing season and the following fall months (planting - 30 November). Bars with the same letter are not significantly different (p>0.10).



In the two year study over 2006 and 2007, tillage and N rate treatments did not significantly affect cumulative nitrate leaching most likely due to the low leaching conditions. Preplanned contrasts were used to further explore the data. All N rates of split urea and emergence PCU were compared and emergence PCU resulted in significantly more cumulative leaching than split urea. Planting PCU resulted in significantly less leaching than emergence PCU at the equivalent N rate, but it could not be compared to split urea. There were no significant differences between planting applied N sources.

The contrasting results in 2005 compared with 2006/2007 are most likely due to differences in leaching conditions. In 2005, leaching occurred early in the season, when soluble urea is more prone to loss than PCU. In 2006 and 2007, N losses mainly occurred later in the season when soil water NO_3 concentrations with emergence PCU were generally higher compared with split urea and planting PCU (data not shown). These results suggest that in years when leaching is high, emergence PCU can reduce NO_3 leaching during the growing season, but it may increase leaching over split urea in years when high N losses occur after harvest. Winter cover crops have been shown to reduce NO_3 leaching following harvest of vegetable crops (Wyland et al., 1996; Brandi-Dorhn et al., 1997) and may be necessary especially following PCU N applications.

Water sampling resumed the following spring after each experiment from ground thaw until the end of April. Averaged over experiments and N rates, soil water NO_3-N concentrations were similar for emergence applied PCU (3 year mean 13.8 ± 8.3 mg L^{-1}), split applied urea (3 year mean 14.6 ± 7.1 mg L^{-1}) and the 0 N control (3 year mean 13.6 ± 7.6 mg L^{-1}). Soil water NO_3-N concentrations previously fertilized with planting applications of PCU and WSPCU in 2006 and 2007 (2 year means 14.4 ± 4.9 and 13.1 ± 9.5 mg L^{-1}, respectively) were generally higher than the 0 N control and planting applied urea (2 year means 9.7 ± 4.7 and 12.3 ± 8.1 mg L^{-1}, respectively). In N treated plots, mean soil water NO_3-N concentrations were above the 10 mg L^{-1} limit, indicating the importance of a subsequent cover crop to reduce NO_3 concentrations and potential leaching.

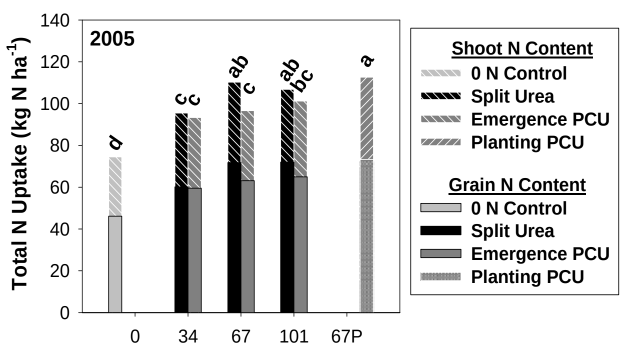
Nitrogen Accumulation in Above Ground Plant Biomass

Nitrogen accumulation in the grain was more than half of the total N uptake in above ground plant biomass in all three years. During this time period, N accumulation in plant biomass (including plants in the 0 N control) was greater than 75 kg N ha^{-1}, suggesting that significant amounts of N were supplied by mineralization and N_2 fixation. Tsai et al. (1993) reported that N_2 fixation and mineralization supplied between 64 – 94% of total N in bean plants at varying soil fertility levels.

In 2005, mean separation tests showed similar results for all variables (shoot, grain and total N accumulation) so only total N uptake is discussed. Over the growing season, N treatments significantly affected total N uptake (Figure 6). The addition of N significantly increased N uptake in above ground plant biomass compared with the 0 N control. Although planting PCU resulted in the highest N accumulation, it was not significantly different from uptake with split urea at 67 and 101 kg N ha^{-1}. With urea applied at emergence and prebloom, N uptake increased as N rate increased to 67 kg N ha^{-1} and then remained approximately the same at the highest rate. Nitrogen uptake did not significantly increase with increasing N rate for emergence PCU. Split urea applications generally resulted in more N accumulation than emergence PCU, but this difference was only significant at 67 kg N ha^{-1}. Split urea also resulted in significantly more NO_3 leaching than emergence PCU. This trend suggests that split applications of urea may have increased N_2 fixation over emergence PCU and therefore more soil water NO_3 was available to plants or to be leached. Planting PCU, however, resulted in higher N accumulation than split urea at the same N rate, and lower NO_3 leaching. While these differences were non-significant, the trend suggests that planting PCU may be more optimal for bean production compared with emergence PCU in leaching years.

In 2006 and 2007, N treatments significantly affected grain N content, but shoot N content was only affected by years. There was a significant N treatment by year interaction for total N uptake. Due to the methodology in PROC MIXED, mean separations tests cannot be performed on interactions that are specified as random, so best linear unbiased predictions (BLUPs) for treatments in each year along with their standard errors are provided in Figure 7. Using contrast statements as suggested in Littell et al. (2006), the interaction was found to be due to differences in emergence or later N applications. In 2006, total N uptake in split urea treatments was significantly higher than emergence PCU treatments, but in 2007, there was no difference between sources at equivalent N rates. There were no differences between N sources when applied at planting in either year.

Figure 6. Total nitrogen (N) uptake in 2005 in above ground plant biomass (shoots + grain). Stacked bars with the same letters are not significantly different (p>0.10) and refer only to total N uptake.



Average shoot N content in 2006 (43.9 kg N ha^{-1}) was significantly higher than in 2007 (25.8 kg N ha^{-1}), but shoot N was not significantly affected by N treatments. The addition of N significantly increased N content in the grain over the zero N control, except the lowest N rate (34 kg N ha^{-1}) of emergence PCU (Figure 8). Grain N content was generally the highest with planting N applications, although grain N uptake with split urea and emergence PCU at 101 kg N ha^{-1} and split urea at 67 kg N ha^{-1} was not statistically different. Overall, planting WSPCU, PCU and urea resulted in similar grain N uptake. Based on a contrast statement comparing all split urea treatments to emergence PCU treatments, the split urea resulted in a significantly higher grain N content than emergence PCU.

Figure 7. The significant N treatment by year interaction for total nitrogen (N) uptake in above ground plant biomass (shoots + grain).

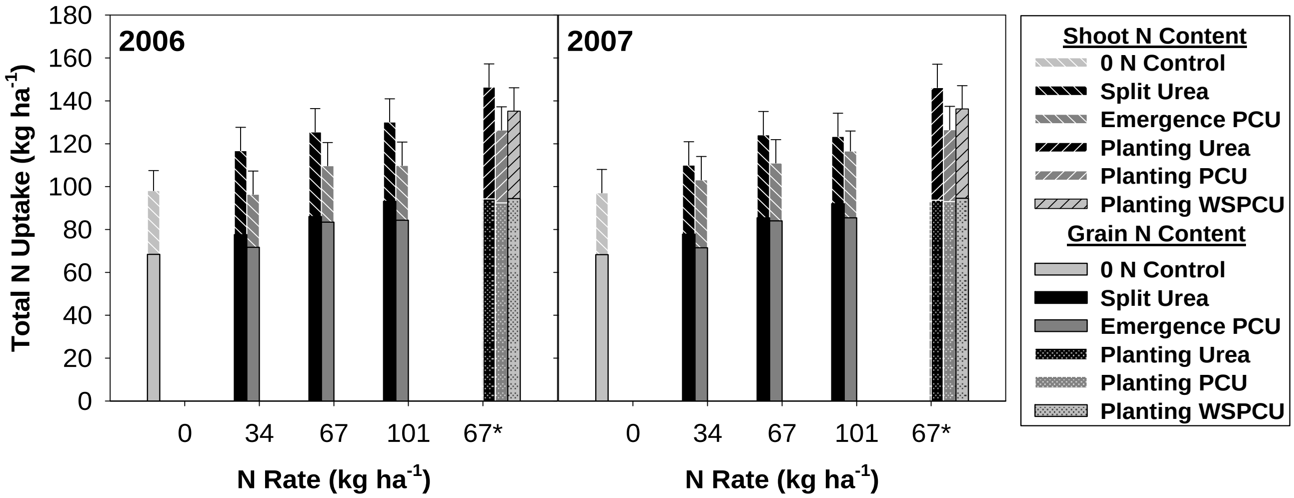
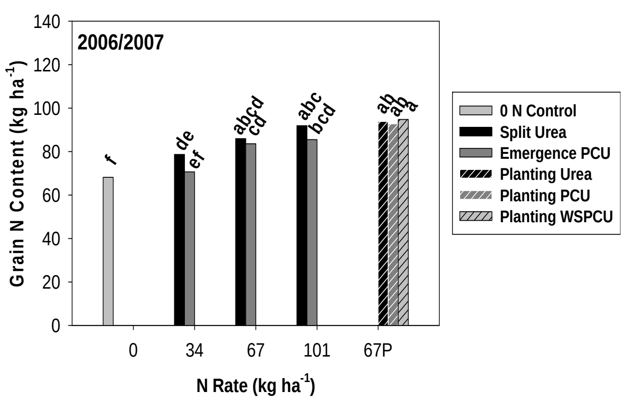


Figure 8. Grain nitrogen (N) content in 2006/2007 as affected by N source, rate and timing. Bars with the same letters are not significantly different (p>0.10).



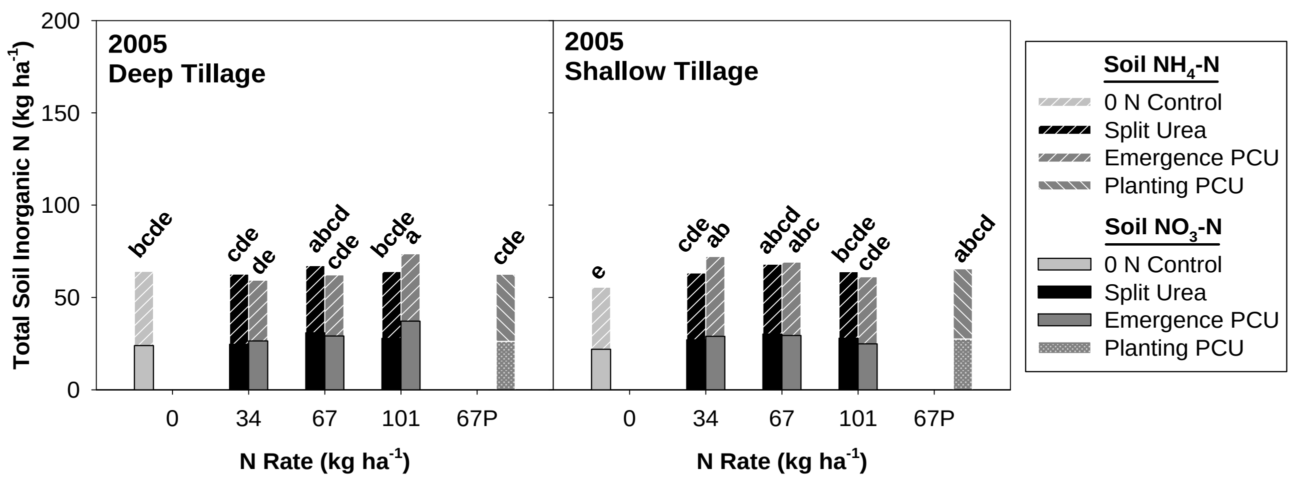
In two dry years, emergence PCU generally resulted in less N accumulation and more NO_3 leaching compared with split urea, although differences were not always significant. Planting PCU, however, typically resulted in similar N accumulation and NO_3 leaching to both planting and split applied urea. Combined with results from 2005, PCU at planting may be more optimal for bean production compared with emergence applications regardless of leaching conditions during the growing season.

Residual Soil Nitrate

In 2005, the tillage by N treatment interaction was significant for total inorganic N in the soil (Figure 9). Soil NO_3-N, however, was not significantly affected by N treatment or tillage or the interaction between the two, so differences in total inorganic N were mainly controlled by differences in soil NH_4-N. With deep tillage, differences between emergence applied N sources were only found at the high N rate, while only the low rate resulted in significant differences in shallow tillage. In both cases, residual soil N was significantly higher with emergence PCU. Total soil N for planting applied PCU was similar to the 0 N control in both tillage treatments.

In 2006 and 2007, soil NH_4 was approximately 66%-75% of total inorganic N. Large leaching events occurred between harvest and soil sampling and may have moved significant amounts of soil NO_3-N past the 60 cm sampling depth. There were significant differences between years for total soil N and soil NH_4-N, but not soil NO_3-N. Total soil inorganic N was 72.9 and 140.9 kg N ha^{-1} in 2006 and 2007, respectively, while soil NH_4-N was 48.0 and 112.4 kg NH_4-N ha^{-1} in consecutive years. Soil NO_3-N averaged 26.9 kg NO_3-N ha^{-1} in both years. Nitrogen treatments and tillage did not significantly affect residual soil inorganic N levels. Other studies that have reported much higher postharvest soil NO_3-N levels compared with the present study. Kimura et al. (2004) reported 61-79 kg NO_3-N ha^{-1} in the top 90 cm of a clay soil after harvest of unfertilized common bean. Meek et al. (1995) also studied unfertilized dry beans and reported 76 and 97 kg NO_3-N ha^{-1} in the top 60 and 90 cm of a silt loam soil after harvest. Soil NH_4-N was not presented in either study. In the current study, it is unclear as to why there was significantly more soil NH_4-N in 2007 compared with 2006, but it is possible that there was more mineralization in 2007. Initial soil samples before planting also show higher soil NH_4-N in 2007.

Figure 9. The interaction between tillage depth and N treatment on total soil inorganic N in the top 60 cm after harvest in 2005. Stacked bars with the same letter (including both tillage depths) are not significantly different (p>0.10).



CONCLUSIONS

This study was conducted to examine the effects of tillage and a PCU on kidney bean production in Minnesota. Under the conditions of this study, tillage treatments did not significantly affect water percolation, plant N accumulation, nitrate leaching or the residual soil inorganic N except in combination with N treatments. During the study period, residual soil inorganic N was not affected by N source, but post-harvest soil N levels were relatively high and may require a cover crop to recover N to reduce NO_3 leaching. In two dry years, WSPCU applied at planting resulted in similar grain N uptake and leaching as planting applied urea and PCU. Under the same conditions, PCU applied at emergence tended to result in lower grain N accumulation and more NO_3 leaching compared with split applications of urea. In a wet year, however, emergence applied PCU significantly reduced NO_3 leaching while plant N uptake was similar to split applied urea treatments. PCU applied at planting resulted in similar plant or grain N uptake as split applied and planting urea at equivalent N rates, and generally reduced NO_3 leaching (although not always significant), regardless of leaching conditions. Combined with grain yield and monetary return data (Wilson, 2008), planting applied PCU has shown promising results for replacing soluble N sources to reduce NO_3 leaching while maintaining yield. Further studies need to test the effect of WSPCU on grain yield and nitrate losses under leaching conditions.

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A Comparison of Techniques for Determining Nitrogen Release from Polymer-coated Urea in the Field

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Additional index words. controlled-release fertilizer, nitrogen release characteristics, mesh bag, potato, weight method

***Abstract*. Although laboratory analyses of nitrogen (N) release from polymer-coated urea (PCU) are available for most brands of PCU, data are lacking for release patterns under field conditions. Release rate studies for PCU are often time-consuming and expensive as a result of the need for multiple chemical analyses. We compared the N release using a weight loss method with a direct chemical analysis method for two types of PCU (Agrium PCU, Agrium U.S. Inc.; Kingenta PCU, Shandong Kingenta Ecological Engineering Co., Ltd.). The PCU prills were placed in a mesh bag and N loss from the prills over time was determined indirectly by loss in weight. The N content of the prills was determined by the combustion method to verify the weight method technique. A second study was conducted to determine if the type of mesh bag material affects the percentage of N released. For this study, mesh bags were constructed from two different materials with two different hole sizes and total amount of open area. Overall, regression analysis suggested that the percentage of N released as estimated by the weight method and combustion method was not significantly different over the growing season for two types of PCU. The mesh bags made of the material with smaller holes and less open area resulted in significantly less N release than the material with more open area and larger holes. Overall, these results suggest that the weight method can be reliably used as a substitute for chemical analysis to determine N release characteristics of PCU, but mesh bag materials must be taken into consideration to reduce errors. The best technique to determine N release may be one that does not include a mesh bag; however, until that method is developed, using a larger hole size is recommended.**

Controlled-release fertilizers are being used more frequently for crop production in an effort to improve plant nitrogen (N) use efficiency and reduce nitrate leaching. Polymer-coated urea (PCU) is a controlled-release fertilizer that releases N over time. The success in improving N use efficiency depends on matching N release with N demand by the crop (Shaviv, 2001). Through manipulation of the coating, manufacturers have control over N release patterns in PCU that can be matched to the uptake of specific crops (Trenkel, 1997), and currently there are a variety of brands available with differing N release characteristics.

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Mention of a trademark, proprietary product, or vendor does not constitute a guarantee or warranty of the product by the University of Minnesota and does not imply its approval to the exclusion of other products or vendors that also may be suitable.
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Although there are many types of PCU available to crop producers, there is a lack of knowledge about N release patterns under field conditions. Conventionally, dissolution of urea in PCU is determined from a static test in which PCU is dissolved in water and the refractive index of the solution is determined as a function of time (Salman et al., 1989). These laboratory measurements are often the only information available to consumers about PCU N release characteristics, although there is generally a lack of correlation between these and field measurements (Trenkel, 1997).

Several studies have reported patterns of N release using varying techniques, but no standardized test exists. Simonne and Hutchinson (2005) used pot-in-pot trials in the field to measure the number of days needed to recover specific amounts of applied N. In that study, leachate samples were collected from the lower pot and analyzed for recovered NO_3-N and NH_4-N. The most common technique, however, is to enclose a known amount of PCU into a bag of porous material and bury it in the field. These mesh bags are removed over time to estimate N loss. However, the type of material used for mesh bags and the determination of N loss varies by study. Pack (2004) used cheesecloth and then ground the PCU prills to dissolve the remaining urea in a known amount of water. The solution was then analyzed by a total Kjeldahl nitrogen method (TKN). Gandeza et al. (1991) and Zvomuya et al. (2003) used plastic mesh and directly analyzed the prills by TKN. Savant et al. (1982) and Salman et al. (1989) used nylon screen and determined the loss of urea by the loss of weight from the prills. Although the two weight loss studies were conducted in soil, they were not conducted under field conditions.

With the exception of the latter two studies, the percentage of N released from PCU was determined with chemical analysis, which can be expensive and time-consuming. The weight method presented in Savant et al. (1982) may reduce the costs of a PCU release rate study, but it has not been validated with chemical analysis.

The reliability of the method also depends on the material used for the mesh bags that enclose the fertilizer. For instance, a proper material should allow the PCU to be exposed to soil and the same moisture conditions that affect the intended crop. A material with hole openings that are too small may reduce exposure, whereas one with large openings may allow fertilizer to fall out of the container.

The objectives of this study were to 1) compare the weight method with direct chemical analysis for determining N release characteristics of PCU; and 2) determine the effect of mesh bag material type on N release from PCU.

Materials and Methods

Field experiments were conducted over the 2007 growing season as part of a larger study to evaluate PCU rate and timing at the Sand Plain Research Farm in Becker, MN. The soil at this site is a Hubbard loamy sand (sandy, mixed, frigid Typic Hapludoll). The experimental crop was 'Russet Burbank' potato (*Solanum tuberosum* L.) planted on 26 Apr. and hilled at emergence on 15 May. The crop was irrigated according to the checkbook method (Wright, 2002). Details of management and cultural practices can be found in Wilson (2008).

Two experiments were conducted: 1) to test methods of determining the percent of N released (%NR) from PCU; and 2) to test the effect of mesh bag materials on N release. Two types of PCU were tested in the first experiment. The first was a 90-d release PCU (44-0-0) marketed as Environmentally Smart Nitrogen from Agrium U.S. Inc. (Denver, CO) (Agrium PCU). The second was a 90- to 120-d release PCU (42-0-0) produced by Shandong Kingenta Ecological Engineering Co., Ltd., (Linyi, Shandong, China) (Kingenta PCU). The release periods listed are those reported by the manufacturer.

The second experiment tested two different types of material for construction of mesh bags. Only Agrium PCU was used in the second experiment. The first material was polypropylene mesh (Industrial Netting, Minneapolis, MN) with 1.2-mm^2 hole openings and a 43% open area (this was also the material used in the first experiment). The second was weedblock landscape material

(Easy Gardener Weedblock Fabric, Waco, TX) from a local hardware store made of polyethylene with a hole size of ≈0.07 mm^2 and an open area of 24%. For both experiments, mesh bags were ≈10 cm × 10 cm and heat-sealed with an impulse sealer (ULINE, Chicago, IL) along three edges. Finally, 3 ± 0.0002 g of PCU (≈174 and 113 prills for Agrium and Kingenta PCU, respectively) were placed in the bags and then the open side was heat-sealed.

The experimental design for both experiments was randomized complete blocks. The first experiment had three replicates, whereas the second experiment had two replicates. Each replicate consisted of 10 bags that were buried in the potato hill and subject to the same temperature and moisture conditions as fertilizer placed in the hill. In Expt. 1, Kingenta PCU was buried in the field 6 d before planting on 20 Apr. to a depth of 5 to 10 cm, because potato hills were not formed until the day of planting. This treatment was intended to simulate a preplant application of PCU. Agrium PCU was buried at planting on 26 Apr. to the depth of the fertilizer band (≈25 cm) to simulate a banded PCU application. Kingenta PCU mesh bags were then transferred to the plots and buried at 5 to 10 cm in the potato hill. Although the dates and placement of mesh bags were different for each material, these differences should not affect achieving the objectives of this study. In Expt. 2, mesh bags of each type were buried on 15 May ≈5 cm below the top of the hill to simulate N release from Agrium PCU applied at emergence. For both experiments, one mesh bag was retrieved from each replicate at ≈2-week intervals until the end of the growing season. Fertilizer prills were air-dried in the mesh bags for a minimum of 14 d before processing. The prills were then removed manually from each mesh bag, separated from soil, and then weighed.

Two different methods were used to calculate %NR over the course of the growing season in the first experiment. The first is a modified technique (Savant et al., 1982) using the change in prill weights over time. First, the weight of the polymer coating in 3 g of PCU was determined using the following equation:

$$F_C = F_i - \left[\frac{F_i * (\%N_{PCU})}{\%N_{urea}}\right] \quad (1)$$

where F_C is the weight of the polymer coating in grams, F_i is the initial amount of PCU in the mesh bags, $\%N_{PCU}$ is the percent of N in the PCU product, and $\%N_{urea}$ is the percent of N in uncoated urea. Based on the manufacturer's N analysis, the weight of polymer coating in 3 g of fertilizer was calculated to be 0.13 and 0.26 g for Agrium PCU and Kingenta PCU, respectively. The %NR for each sampling date was then determined by the following equation:

$$\%NR_W = \left[1 - \left(\frac{F_s - F_c}{F_i - F_c}\right)\right] * 100 \quad (2)$$

where $\%NR_W$ is the percent of N release as determined by the weight method, F_s is the weight of the PCU on the sampling date, F_c is the weight of the polymer coating, and F_i is the initial amount of PCU in the mesh bag.

For the second method, %NR was determined by chemical analysis. Fertilizer prills from each sampling date were air-dried, crushed in a mortar and pestle, and then N was determined using a combustion analyzer (LECO FP-528 Total Nitrogen Analyzer; LECO, St. Joseph, MI) following the general methods for plant material in Horneck and Miller (1998). The N found by combustion was multiplied by the weight of the prill sample to determine N content remaining in the prills. The %NR for each sampling date was then determined by the following equation:

$$\%NR_C = \left[1 - \left(\frac{N_s}{N_i}\right)\right] * 100 \quad (3)$$

where $\%NR_C$ is the percent of N release as determined by the combustion method, N_s is the N content in grams of the PCU on the sampling date, and N_i is the initial N content in 3 g of PCU as determined by combustion. The actual N concentration in the prills on Day 0 before mesh bag burial was 44.5% ± 0.2% for Agrium PCU and 42.8% ± 0.6% for Kingenta PCU based on combustion analysis. Only the weight method was used to determine %NR in the second experiment.

Pearson correlation coefficients in PROC CORR were used to determine the association between the weight and combustion methods of calculating %NR and PROC REG was used to fit a linear regression line to the data (SAS Institute Inc., 2004). To further compare the two methods in each experiment, %NR was also plotted as a function of days after planting (DAP). On the day that mesh bags were buried, N release was assumed to be zero. Regression models were fit for each treatment and analyzed in PROC MIXED (SAS Institute Inc., 2004). This method compares intercept and slope coefficients of lines to determine if they are statistically different. Coefficients were considered significantly different at probability levels less than 5%.

Results and Discussion

Expt. 1: Methods to determine percent nitrogen release from polymer-coated urea. The weight and combustion methods of determining the percent of N release (%NR) were highly correlated ($P < 0.0001$) for both Agrium and Kingenta PCU with correlation coefficients greater than 0.999 (Figs. 1 and 2, respectively). For both PCUs, the slope of the regression line was also near 1 ± 0.05. This indicates that the %NR on each sampling date was at an approximate 1:1 ratio, which also means that predicted %NR by each method was similar at every sampling date. A slope below or above 1 would imply that one method produced higher or lower values than the other method.

To further explore if N release found by each method was similar, equations were fit to each data set as a function of DAP. For Agrium PCU, a quadratic equation modeled the response of N release rate with time (Fig. 3). Gandeza et al. (1991) and Zvomuya et al. (2003) also reported a quadratic release model for %NR of a different PCU. For Agrium PCU, the slope and intercept coefficients from each method were not significantly different ($P > 0.10$). Percent N release peaked at ≈97% between 135 and 140 DAP. Nitrogen release from PCU most likely reached a plateau after this point because

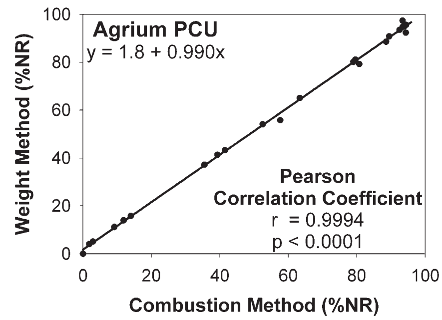

Fig. 1. The correlation between two different methods for determining percent N release (%NR) for Agrium polymer-coated urea (PCU) incubated at the fertilizer band depth of the potato hill. Each point represents one paired observation.

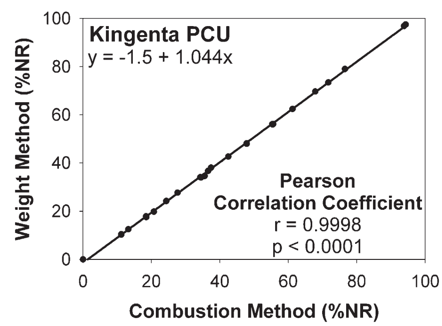

Fig. 2. The correlation between two different methods for determining percent N release (%NR) for Kingenta polymer-coated urea (PCU) incubated at the fertilizer band depth of the potato hill. Each point represents one paired observation.

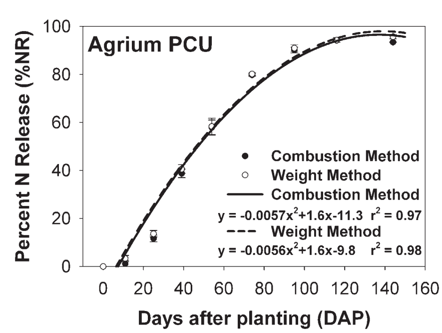

Fig. 3. Percent of nitrogen release (%NR) as a quadratic function of days after planting (DAP) for Agrium polymer-coated urea (PCU) incubated at the fertilizer band depth of the potato hill. Each point represents the mean and 1 SE.

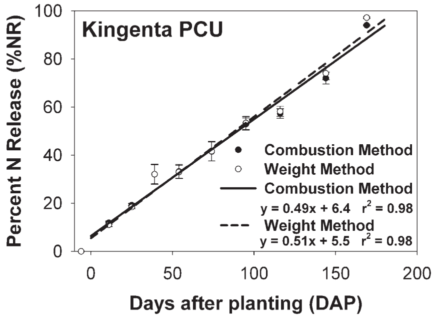

Fig. 4. Percent of nitrogen release (%NR) as a linear function of days after planting (DAP) for Kingenta polymer-coated urea (PCU) incubated at the fertilizer band depth of the potato hill. Each point represents the mean and 1 SE.

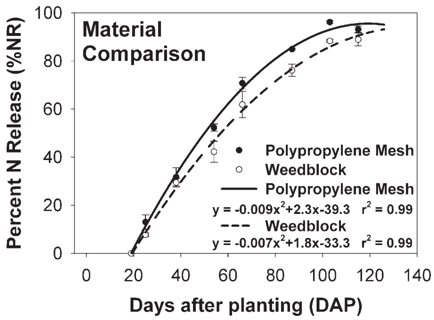

Fig. 5. Percent of nitrogen release (%NR) as a quadratic function of days after planting (DAP) for Agrium polymer-coated urea (PCU) as influenced by mesh bag material. Each point represents the mean and 1 SE.

the fertilizer cannot release more than 100%. For Kingenta PCU, %NR was found to be a linear function of DAP (Fig. 4). Again, the slope and intercept were not significantly different between methods. The linear response suggests that the peak %NR had not been reached by the last sampling date. Both methods resulted in similar %NR over time for the two different types of PCU, although N release patterns varied between N sources. This provides strong evidence that the weight method can be considered a good predictor of N release for the products evaluated. Depending on the coating, there is potential for some PCU products to retain water when air-dried, which would affect the weight and underestimate N release using the weight method. However, we did not encounter this as being a problem in the present study.

Expt. 2: Mesh bag material comparison. The N release of Agrium PCU from two different types of mesh as a function of DAP was found to fit a quadratic model (Fig. 5). The linear coefficients of each line were significantly different for each material ($P < 0.05$). The quadratic coefficients were not different at $P = 0.05$, although a trend was noted at $P = 0.07$. The constant coefficients, or intercept, were not significantly different for each material ($P > 0.10$). Initially, %NR with both types of mesh bags appears to be similar, but after 40 DAP, %NR with weedblock was lower than with polypropylene mesh. After removing mesh bags from the potato hill, prills in the weedblock bags were typically cleaner than prills in polypropylene. This suggests that the polypropylene mesh allowed prills to come in closer contact to the soil compared with weedblock bags and may explain the difference in %NR. Because PCU prills are in complete contact with the soil when applied to crops, polypropylene mesh may provide a better estimate for actual N release in the soil than weedblock bags. Pack (2004) used cheesecloth as a material for mesh bags, which would also prohibit contact with the soil, but the methods in that study required 200 g of soil to be placed in the bags with the fertilizer. Although this may solve the problem of prill contact with soil, removing the prills from the soil may be more time-consuming and it is unclear if water movement into the bag would be affected. When developing a standard procedure for N release from PCU, further research should consider the effect of mesh bag materials or if inclusion of soil in the bag further enhances N release. The best technique for determining N release characteristics of PCU in the soil may be one that does not include a mesh bag. However, until that technique is further developed, using the largest possible hole size is recommended.

Conclusions

The N release characteristics of two PCUs were determined with the weight method and by combustion analysis. Both methods resulted in the same percent N release over time for both N sources, which suggests that the mesh bag weight method can be reliably used for determining PCU N release characteristics. The effect of mesh bag material on N release of PCU was also examined. Weedblock material, which has smaller hole openings and less total open area, resulted in significantly lower N release over the growing season than a polypropylene mesh with larger hole openings and more open area. The difference between materials was most likely the result of hole size, which restricted the interaction between soil and fertilizer. When conducting mesh bag experiments to determine N release characteristics of a PCU, it is important to choose a material that will not limit exposure to water and soil.

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Costs of Groundwater Nitrate Contamination:

A Survey of Private Well Owners in Central Minnesota

A.M. Lewandowski, B.R. Montgomery (MN Dept. of Agriculture), C.J. Rosen, and J.F. Moncrief

This fact sheet is a summary of: A.M. Lewandowski, B.R. Montgomery, C.J. Rosen, and J.F. Moncrief. 2008. Groundwater nitrate contamination costs: A survey of private well owners. *Journal of Soil and Water Conservation* (2008. 63:153-161).

Background and methods

More than 70% of Minnesotans get their drinking water from groundwater, including more than one million people who rely on private wells. Statewide, 5% to 10% of drinking water wells have nitrate-N (NO_3-N) concentrations that exceed the health standard of 10 ppm (mg/L)[1]. Risk of contamination increases in areas of sandy glacial outwash deposits where drinking water is often drawn from surficial aquifers, i.e., aquifers above bedrock with no clay or rock confining layer protecting them from contaminants in surface recharge water. Methods for assessing the extent and magnitude of contamination are limited, and little is known about well owners' responses to documented or perceived NO_3 contamination.

With the presence of NO_3, well owners may incur direct costs related to treatment systems, well replacement, and purchasing of bottled water. The objective of this study was to quantify actual amounts spent by private well owners in the glacial outwash soils of Minnesota in response to elevated NO_3. Understanding these direct costs of NO_3 contamination can help planners justify and allocate the costs of preventing contamination through education, technical support, and financial incentives. The study also demonstrates a low-cost method for representative sampling of private wells. Well owners were identified using county land parcel lists, and water samples were collected using mailed NO_3 test kits rather than on-site visits.

We mailed questionnaires to 800 private well owners in the central sand plains of Minnesota. The survey asked about well characteristics, NO_3 testing, and costs of actions taken in response to elevated NO_3. The response rate was 60%. Respondents were sent water sample bottles, of which 77% were returned for nitrate testing.

[1] Minnesota Pollution Control Agency. 2006. Chapter 9: Agricultural nutrients. In Minnesota's Nonpoint Source Management Program Plan. http://www.pca.state.mn.us/water/nonpoint/mplan.html

Well characteristics

Fig.1. "How deep is your well?"

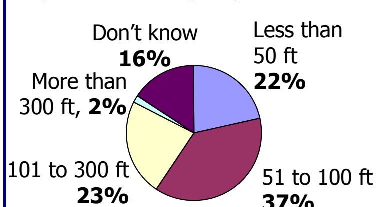


Fig.2. "How old is your well?"

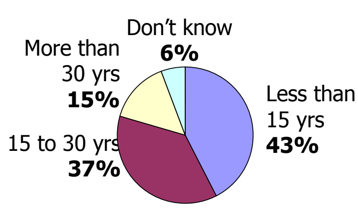
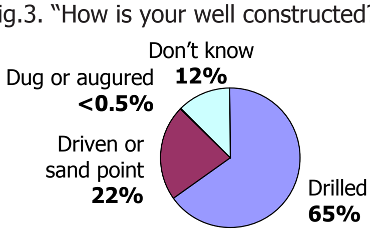


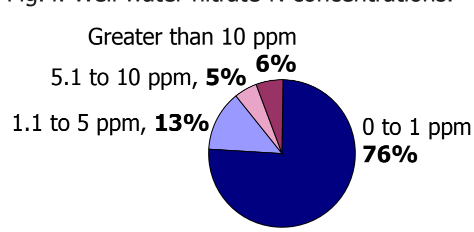
Fig.3. "How is your well constructed?"



Sand point wells are becoming less common. Of wells more than 30 years old, 53% are sand points and 27% were drilled. Of wells less than 15 years old, only 9% are sand points and 79% were drilled.

About 6% of wells had greater than 10 ppm NO_3-N – a rate comparable with results from other studies in Minnesota. Surprisingly, the prevalence of high-NO_3 wells did not differ between sand point and drilled wells. Elevated NO_3 concentrations were more common in wells where the principal land use within a quarter mile was agricultural and in wells greater than 30 years old.

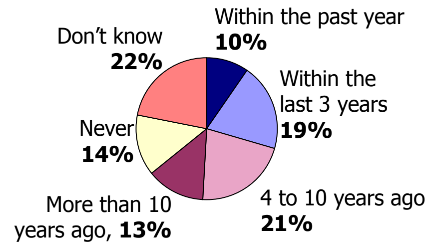
Fig.4. Well water nitrate-N concentrations.



Well water testing

The Minnesota Department of Health recommends a routine NO_3 test every two to three years for private wells used for drinking water. Only 29% of those surveyed had tested their well within the past three years. Of the remainder, two-thirds did not feel a need to test because either they did not drink the water, the water was filtered, or they presumed the water was fine. Some were not aware that their carbon filters and water softeners do not remove NO_3. Cost and inconvenience were less common barriers to testing.

Fig. 5. "When was your drinking well water last tested for nitrate?"



Responses to elevated nitrate-N and costs

The average cost of NO_3 contamination is $89 per year per well. This was calculated by multiplying the prevalence of each action among the owners of >10 ppm NO_3-N wells by the cost of the action. The initial cost of a treatment system was spread over 20 years, and the cost of a well was spread over 50 years. We subtracted out spending by people with 0 to 2 ppm NO_3-N (data not shown) since their spending would occur even without NO_3 contamination.

	Actions reported by all respondents (N = 483)	Actions reported by owners of >10 ppm NO_3-N wells (N = 33)	Average initial cost	Average annual cost
NO_3 removal system	7.5%	21.9%	$800	$100
Bottled water[§]	10.4%	25.0%		$190
New well	1.7%	25.0% [#]	$7200	
Nothing	83%	37.5% [†]		

[§] Only includes those who drink bottled water in response to elevated NO_3. Additional people drink bottled water for other reasons.
[#] All 8 respondents who said they installed a new well because of elevated NO_3 were included in this high NO_3 group, even though their water sample (from the new well) tested low for nitrate.
[†] At the time of the survey, most of this group did not know their NO_3-N concentration was >10 ppm.

Perceptions of water quality

Although water testing rates are low, most homeowners are concerned about water quality and feel they have ample opportunities to learn about their water quality.

Fig. 6. "Do you agree with the following statements?"

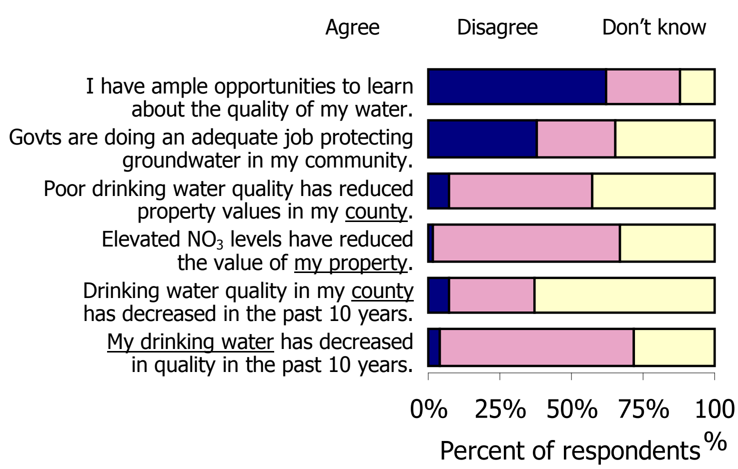
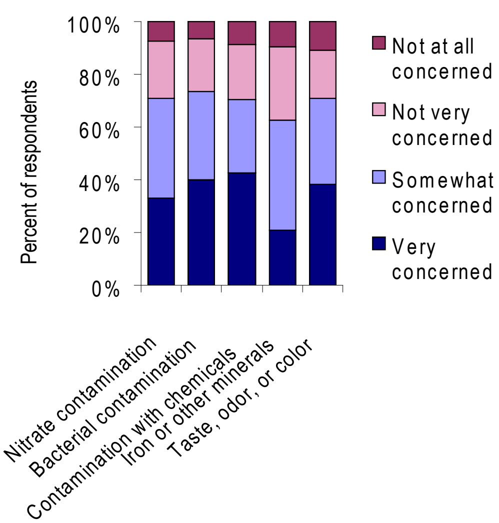


Fig. 7. "How concerned are you about the following water quality issues related to your drinking water?"



For Further Information

Minnesota Department of Health – www.health.state.mn.us/divs/eh/water/index.html
Minnesota Department of Agriculture – www.mda.state.mn.us/protecting/waterprotection/drinkingwater.aspx

Funding for this project was provided in 2005 by The Environment and Natural Resources Trust Fund as recommended by the Legislative Commission on Minnesota Resources (LCMR).

Sept 2010

UNIVERSITY OF MINNESOTA
Department of Soil, Water, and Climate

Costs of Groundwater Nitrate Contamination: Municipal Water Suppliers

A fact sheet for city council members, legislators, and
other decision makers interested in protecting local drinking water.
Full report available at http://www.mda.state.mn.us/protecting/waterprotection/drinkingwater.htm.

Concerns about Nitrate in Minnesota Groundwater

Over 75% of Minnesotans get their drinking water from groundwater; and once an aquifer is contaminated, it may be difficult or impossible to clean. Nitrate in groundwater contributes to "Blue Baby Syndrome" – a reduction in the blood's ability to carry oxygen when infants consume contaminated water. Clean water is essential for sustaining the long-term social, economic, and environmental health of our communities.

Some Minnesota communities are facing the problem of nitrate contamination. According to Minnesota Department of Health (MDH) data from 1999 to 2004, nitrate-N concentrations above 3 mg/L (or ppm) were measured by 64 communities serving 226,000 people and 24 non-municipal suppliers (e.g. mobile home parks). Concentrations above 1 to 3 ppm indicate human activities have affected the groundwater. Several of these communities already incur costs, and others may face future costs as they take steps to keep drinking water nitrate-N levels below the 10 ppm health standard.

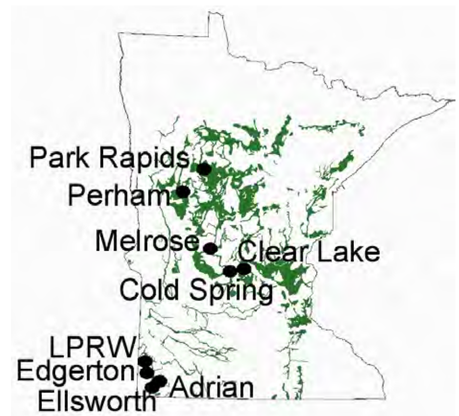
This fact sheet summarizes information from interviews with community water suppliers that currently have expenses directly related to nitrate contamination. They serve communities of 400 to 3700 people. Acknowledging that every community's expenses are unique, planners can use this information to anticipate future costs and estimate the economic value of preventing nitrate contamination.

We All Pay for Nitrate Contamination

The costs of nitrate contamination are paid by:

- Municipal water customers who pay increased rates to treat well water or find an alternative source.
- Consumers who may suffer health effects.
- Taxpayers, when a community loses businesses or real estate value because of low water quality.
- MDH (i.e., taxpayers) which monitors suppliers and enforces Federal Safe Drinking Water Standards.
- Future generations who have fewer options for drinking water sources.

Figure 1. Sandy outwash regions of Minnesota and the cities surveyed for this study.



Costs of Nitrate Contamination to Nine Municipalities

Below are examples of expenses reported by nine water suppliers (fig. 1). Expenses for other communities may differ. This list only describes direct expenses and does not account for health effects or losses to the tax base that may occur if nitrate contamination limits business opportunities.

Short-term management includes legal requirements such as notifying residents of high nitrate concentrations and increasing the water monitoring schedule. Other potential expenses not reported by any of the survey cities may include remediation of contamination, litigation or legal opinions, consulting and engineering fees, increased insurance costs, or decreased property values.

$360 to $4,000 for a notification or education campaign

New well expenses may include exploratory drilling to find a clean aquifer, systems to remove minerals found in deep aquifers, land purchases, drilling and installation of the new well, and sealing of the old well.

$3,000 to $19,000 for test wells
$160,000 to $250,000 to install and house a new well
$2 mil. to $6 mil. to install iron and manganese removal plant
$3,000 to seal old well

Treatment systems – One water supplier in Minnesota uses reverse osmosis (RO), and five use anion exchange (AE) systems. Below are costs for AE; RO costs may be three times greater.

$350,000 to $600,000 for initial construction
$1,600 to $12,000 annually for salt
$2,600 to $9,600 annually for energy
$450 to $900 annually for regular nitrate testing
$600 to $5,400 annually for regular maintenance
$0.82 to $2.25 total extra costs per 1000 gals., excluding labor

Well blending – If a city has multiple wells with different nitrate concentrations, they may blend water from the wells to produce finished water that is safe. Examples of annual costs include:

$3,000 annually for the labor to monitor and switch pumps
$1,000 annually for frequent lab tests to monitor nitrate concentrations

The Alternative: Wellhead Protection

Nitrate removal systems treat water but do not solve the contamination problem. Implementing wellhead protection measures to prevent nitrate contamination can eliminate the need for water treatment, or at least reduce treatment costs. It also protects drinking water from a wide range of potential contaminants.

Wellhead protection planning relies on continued technical support from MDH, MRWA, MDA, and conservation districts. MDH and MRWA provide extensive staff time on every wellhead protection plan.

City water managers identified the following barriers to effective wellhead protection from nitrate contamination.

- Uncertainty about when and how much of a benefit to expect from protection activities.
- Competition with other budgetary concerns and protection of other natural resources.
- Lack of authority by the city over the recharge area for their wells. Cities must depend on local zoning authority, on state and county enforcement of rules governing nitrate sources, and voluntary cooperation from farmers, homeowners, developers, and other land owners.
- Most conservation programs are designed primarily to protect soil and surface water and are less effective for protecting groundwater. For example, the federal Conservation Reserve Program defines the eligible wellhead protection area in terms of a radius around the well rather than in terms of actual underground hydrology. In some cases, incentive payments may not be adequate to allow farmers to take highly productive farmland out of production.

Actions for Local Planners

- Aquifer contamination is persistent, so protection should be a high budgetary priority in land use and water resource planning.
- Determine the benefit of prevention by estimating potential costs of contamination.
- Contact MDH and MRWA for help developing a wellhead protection plan.
- Integrate groundwater protection activities across agencies and political jurisdictions.

Actions for Policy Makers

- Increase consideration of groundwater protection when designing and implementing conservation programs, especially when defining eligible land and cost share payments.
- Account for groundwater protection in local zoning and land use planning policies.
- Continue support for MDH and MRWA source water protection activities.

For more information:

Minnesota Department of Agriculture (MDA) www.mda.state.mn.us/protecting/waterprotection/drinkingwater.htm.
Includes the full version of this report and a report of costs to private well owners.

Minnesota Department of Health (MDH) www.health.state.mn.us/divs/eh/water/swp

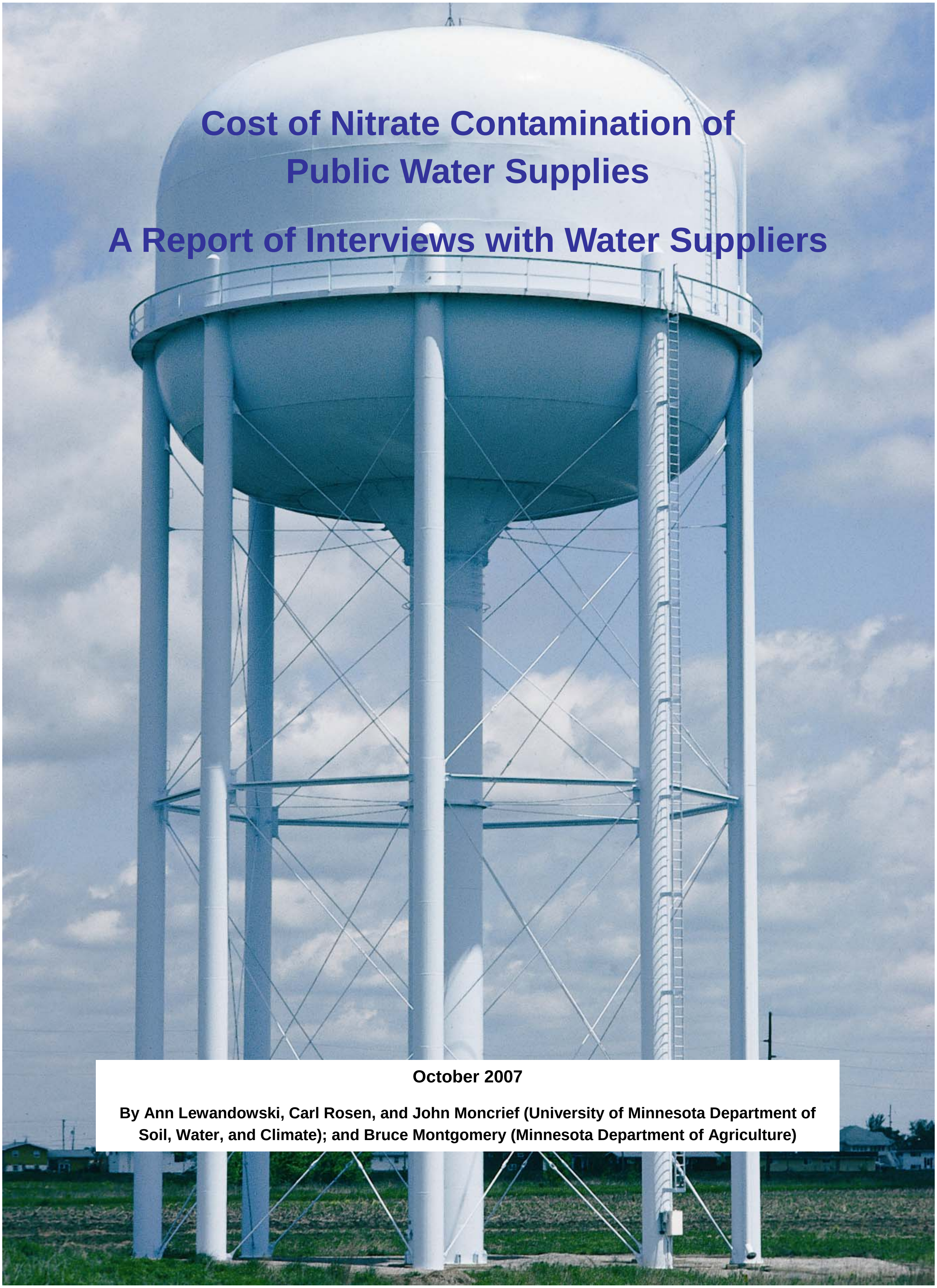
Minnesota Pollution Control Agency (MPCA)
Ground Water in Minnesota: www.pca.state.mn.us/water/groundwater/
Clean Water Partnership Program: www.pca.state.mn.us/water/cwp-319.html

Minnesota Rural Water Association (MRWA) www.mrwa.com/sourcewater.htm

A report by the University of Minnesota Department of Soil, Water, and Climate with technical assistance from the Minnesota Department of Agriculture, Minnesota Department of Health, and the Minnesota Rural Water Association. Special thanks go to the city water managers and other city officials who provided information for this study. Funding was provided by The Environment and Natural Resources Trust Fund as recommended by the Legislative Commission on Minnesota Resources (LCMR). *September 2007*

Cost of Nitrate Contamination of Public Water Supplies

A Report of Interviews with Water Suppliers



October 2007

By Ann Lewandowski, Carl Rosen, and John Moncrief (University of Minnesota Department of Soil, Water, and Climate); and Bruce Montgomery (Minnesota Department of Agriculture)

Cost of Nitrate Contamination of Public Water Supplies:

A Report of Interviews with Water Suppliers

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October 2007

A report by the University of Minnesota Department of Soil, Water, and Climate with technical assistance from the Minnesota Department of Agriculture, Minnesota Department of Health, and the Minnesota Rural Water Association. Special thanks go to the city water managers and other city officials who provided information for this study.

This and other reports about costs of nitrate contamination are available from the Minnesota Department of Agriculture at http://www.mda.state.mn.us/protecting/waterprotection/drinkingwater.htm.

Funding for this project was provided by The Environment and Natural Resources Trust Fund as recommended by the Legislative Commission on Minnesota Resources (LCMR) (MN Laws 2005 First Special Session, Chapter 1, Article 2, Section 11, Subd. 07i).

Summary

Responding to groundwater nitrate contamination is costly and can be a significant financial burden on small towns. For this study, managers from seven Minnesota cities were interviewed and data for two additional cities was reviewed to learn how much they spent in response to nitrate contamination. The purpose was to help other towns anticipate potential expenses and justify wellhead protection activities that prevent contamination.

The installation and maintenance of municipal nitrate removal systems increase the cost of water delivery by fourfold or more. This translates into $100 to $200 more per customer per year. Even before a treatment system is installed, cities pay for elevated groundwater nitrate concentrations through increased costs of siting a new well, more frequent nitrate testing, and blending water from multiple wells.

Communities may incur additional costs not beyond those of supplying water. These include costs of health effects, devalued real estate, and the loss of future development if development is deterred by the contaminated water supply.

Cities with rising nitrate concentrations may be able to avoid spending the $400,000 – or much more – needed to install a treatment system by working now to protect their aquifer from nitrate contamination. The challenge is to motivate numerous stakeholders to take actions that will have an uncertain result and may not pay off for years. Because well capture areas (wellhead protection areas) often extend outside of city limits, cities have few tools to influence land use and to permanently protect the well capture area. Existing conservation programs are generally designed to protect habitat and surface water and often are poorly suited to protecting groundwater quality.

Treatment systems are only temporary solutions to maintaining drinking water quality. Wellhead protection can prevent the need for a treatment system or reduce the cost of treatment if a system is in use. In addition, wellhead protection prevents other types of contamination and protects an essential natural resource.

Background

Nitrate Contamination in Minnesota

One of Minnesota's most valuable water resources are the aquifers that supply drinking water to over 70% of the state's residents. Nearly all of the state's 954 community water supply systems use groundwater, and some have nitrate concentrations elevated above natural background levels. According to a Minnesota Department of Health dataset from 1999 to 2004, nitrate-N concentrations were above 3 mg/L (or ppm) in the water supplies for 64 communities serving 226,000 people and 24 non-municipal suppliers (e.g. mobile home parks). Unless groundwater protection steps are taken, these communities may face rising nitrate concentrations in the future. According to the same dataset, nitrate-N concentrations exceeded the health standard of 10 mg/L in 12 communities and 4 non-community suppliers delivering water to 47,000 customers.

Nitrate (NO_3^-) moves readily through the soil and is odorless and tasteless in water. The primary health concern of elevated nitrate in drinking water is "Blue Baby Syndrome" (methemoglobinemia) caused when nitrate-contaminated water is consumed by infants under six months of age. In an infant's stomach, nitrate is converted to nitrite which binds to hemoglobin, preventing the blood from carrying oxygen. In rare cases, adults have been poisoned by nitrate, but not by amounts consumed in drinking water. In addition, some research has suggested that long-term consumption of nitrate is associated with certain cancers, but evidence is unclear (Fewtrell, 2004; Rademacher, 1992; Ward et al., 1996). Nitrate is easy to measure in drinking water and can serve as an indicator of risk that other contaminants from human activities are leaching through the soil and into groundwater.

Nitrate Sources

In Minnesota, natural background concentrations of nitrate-N in groundwater generally are less than 1 mg/L (MPCA 2006, 1998). Higher concentrations are generally caused by the leaching of nitrate from fertilizer applications, manure, or human waste (sewage or septage). Other sources of nitrate include atmospheric deposition (e.g., nitrous oxides from combustion) and the decay of plant and animal matter. The amount of nitrate in groundwater depends on the amount of nitrate from all sources, the transport of nitrate through the soil, and the time and location of sampling.

In Minnesota, the three areas most susceptible to contamination are 1) the karst regions of eastern and southern Minnesota; 2) areas of sandy glacial outwash deposits, sometimes over loamy glacial till or lake sediments in central Minnesota; and 3) the sandy river channel aquifers in southwestern Minnesota. This study focuses on areas of sandy glacial deposits where wells often draw drinking water from surficial aquifers, i.e., aquifers near the land surface with no clay or rock confining layer protecting them from contaminants in surface recharge water.

Estimating Costs of Nitrate Contamination

Costs of contamination include the costs of using the contaminated water (e.g., effects on health or industrial activities), and the costs of responding to the contamination, including restoring the aquifer quality (often not feasible), containing a plume of contamination, or avoiding the contaminated water through treatment or an alternative water source (Raucher, 1983). These costs can be estimated by calculating either 1) the “avoidance cost”, that is, costs incurred to monitor, treat, or replace the water source; or 2) the “contingent value” based on asking people what they are willing to pay for an uncontaminated drinking water supply. Contingent value studies of the value of groundwater protection are discussed in Phillips et al. (1999) and Poe et al. (2000), but the results are not readily translated into an estimate of costs in Minnesota. The avoidance cost method does not incorporate all ecological damages or nonuse values of water quality, so it can be considered a low-end estimate of people’s willingness to pay or of the total costs of contamination (Abdalla, 1994). Intrinsic or non-use benefits of groundwater include retaining the option to have a clean aquifer at some time in the future. The value of non-use benefits is not trivial, given the difficulty of reversing groundwater contamination (Raucher, 1983).

Estimating health costs is controversial because the nitrate standard incorporates a safety factor. Thus, small or occasional exceedances of the standard will likely have little observable impact on health costs (Giraldez and Fox, 1995; Addiscott and Benjamin, 2004).

The Freshwater Foundation (1989) studied the costs of groundwater contamination to Minnesota companies and cities. The study was limited to industrial waste or hazardous materials, but the categories of potential costs identified are also relevant to nitrate contamination. They include:

- New equipment, treatment, and direct cleanup
- Increased monitoring
- Increased energy usage
- Increased operation and maintenance costs
- Staff time
- Consulting and legal fees
- Increased water rates
- Devalued real estate
- Diminished home or commercial real estate sales
- Relocation of current businesses or loss of future commercial development and jobs
- Loss to tax base

The current study begins to summarize some of these costs in relation to groundwater nitrate contamination of Minnesota municipal water supplies.

Study Methods

The purpose of the study was to help communities anticipate the costs they may face if groundwater nitrate concentrations rise, and thus to quantify the value of groundwater protection. The study only considered direct expenses to municipalities and did not consider health or environmental effects of nitrate contamination. Because each community’s situation is unique, results are reported qualitatively and as cost examples to help other cities interpret how the results relate to their situation.

The primary source of data was interviews with water supply managers in seven Minnesota communities in the summer of 2006. The managers were first sent extensive questionnaires asking about expenses associated with monitoring, treating, or finding an alternative to nitrate-contaminated drinking water. Open-ended, in-person interviews were conducted to clarify answers to the questionnaire and to discuss wellhead protection issues.

Initially, the communities were selected from among those in central Minnesota with nitrate-N concentrations above 5 mg/L. Only five of these communities were identified as currently incurring costs associated with nitrate contamination (Park Rapids, Perham, Melrose, Clear Lake, and Cold Spring). Two additional communities (Ellsworth and Edgerton) were interviewed in southwestern Minnesota where geologically sensitive aquifers are used. Two other communities with treatment systems (Adrian and Lincoln-Pipestone Rural Water) were not interviewed for this study but were included by using data from a previous study of nitrate treatment systems (MDA and MDH) and from other interviews (Diego Bonta, personal communication). Characteristics of the communities are summarized in Table 1and their locations are shown in Figure 1.

To help other communities assess the potential costs of their unique situation, costs are presented as examples rather than averages.

Table 1: A sample of community water suppliers incurring costs of nitrate contamination.

	Population served	Million gallons supplied annually	1000 gallons /person/year	Nitrate management	Size of DWSMA [a]
Adrian	1200	50	42	Anion exchange system	3 sq mi.
Clear Lake	414 (2006)	15.6 (2005)	32	Anion exchange system, well blending	½ sq mi
Cold Spring	3,693 (2005)	202	55	High nitrate wells go nearly unused	7 sq mi
Edgerton	1030 (2006)	45 (2005)	44	Anion exchange system	1 sq mi
Ellsworth	540	17	30	Anion exchange system	5 sq. mi.
Lincoln-Pipestone Rural Water -- Holland Well Field	1062 (2004)			Reverse osmosis system	37 sq. mi.
Melrose	3091 (2003)	697 (2005) (85% goes to agr. industries)	225	Well blending	2.9 sq mi
Park Rapids	3275	215	65	Well blending	4 sq. mi.
Perham	2726 (2006)	326 (2005) (50% goes to industries)	120	Well blending	18 sq mi

[a] Drinking Water Supply Management Area – see glossary.

Figure 1: Sandy outwash regions of Minnesota and study cities.

Map shows areas with the attribute "Outwash – Undivided as to Moraine Association" from Hobbs and Goebel (1982).

Examples of Costs of Contaminated Groundwater

Once the nitrate-N level in a drinking water source rises above 10 ppm, a community water supplier must either treat the water or find another source. The following is a list of potential expenses and examples of costs incurred by Minnesota communities.

Short term management

If nitrate-N in drinking water rises above 10 ppm, the water supplier must notify all residents and provide an alternative water supply, such as bottled water. The following are examples of costs for responding to a single event.

$360 **Clear Lake, notifications**

$250 **Edgerton, postings and media announcements**

$4,000 **Melrose, notifications and education**

Other potential costs include remediation of a contaminated site, litigation or legal opinions, consulting and engineering fees, increased insurance costs, and decreased property values. None of the cities in this study reported any of these costs.

New well

When an aquifer is contaminated with nitrate, siting a new well becomes more expensive because multiple test wells may need to be drilled to locate a clean aquifer.

Deep aquifers are often a preferred water supply because they are less susceptible to nitrate contamination. However, water from deep aquifers is more likely to require treatment to remove higher concentrations of iron, manganese, sulfate or naturally occurring contaminants such as arsenic or radium. Removal systems for naturally occurring ions or contaminants may initially cost about the same as nitrate removal systems, but their life expectancy is generally longer and operating and maintenance costs are lower.

Examples of expenses associated with a new well:

- Test wells to identify a site without excess nitrate.

  $5,500 Park Rapids, two test wells (2005)

  $16,000 to $19,000 each Clear Lake, three test wells (2003 and 2004)

  $3,000 Edgerton, test wells (2001)

- Land purchase

- Drilling, pump installation, well housing

  $162,000 Park Rapids, to drill a pair of wells (2005 estimate)

  $246,300 Clear Lake (2004)

- Treatment systems to remove iron, sulfur, or radon

  $2,010,000 Park Rapids, Fe and Mn removal plant, including building (2005 estimate)

  $5,000,000 to $6,000,000 Melrose, Fe and Mn removal plant, not associated with drilling a new well (2006 estimate)

- Sealing an old well

  $3,000 Melrose

Reverse osmosis (RO) treatment system

In an RO system, water is forced through a semi-permeable membrane leaving behind a large proportion of high-nitrate waste water. Costs of running an RO system increase if mineral concentrations are high. Only one municipal RO system is operating in Minnesota.

Expenses include:

- Initial construction. RO systems are expected to last about 20 years.

  $1,706,650 Lincoln-Pipestone Rural Water (1999)

- Annual operating and maintenance costs, including electrical power for the pumps and replacement membranes.

  $31,000 Lincoln-Pipestone Rural Water (maintenance including membranes)

  $36,000 Lincoln-Pipestone Rural Water (energy)

- Waste water disposal.

  Lincoln-Pipestone Rural Water disposes of 1 gallon of waste water for every 5 gallons used.

Anion exchange treatment system

Anion exchange (AE) systems remove nitrate by replacing the negative nitrate ion (NO_3^-) with the negative chloride ion (Cl^-) from salt. Water softeners do not remove nitrate because they replace positive ions (e.g. Fe^{+++}) with the positive sodium (Na^+) ion from salt. Examples of costs of AE systems are shown in Table 2. The initial construction costs depend partly on the amount of water to be treated, whereas operating and maintenance costs depend on the amount of nitrate removed which determines the amount of salt required. Costs can be reduced by increasing the nitrate concentration in the final treated water, or by lowering the nitrate concentration in untreated water through wellhead protection activities. For example, the City of Edgerton estimates that salt usage could double if nitrate-N concentrations in their untreated water rose from the current value of 7-9 ppm up to 10-12 ppm, which was the nitrate-N concentration before land in the well recharge area was enrolled in agricultural set-aside programs. Salt usage in Clear Lake dropped after a new low-nitrate well came on line in 2005.

Table 2: Examples of annual costs for anion exchange treatment systems

	Clear Lake	Edgerton	Ellsworth	Adrian
Population served	414 (2006)	1,030 (2006)	540	1,200
Million gallons supplied	15.6 (2005)	45 (2005)	17	50
Initial construction[a]	$412,390 (1995)	$352,000 (2003)	$362,000 (1994)	$601,000 (1998)
NaCl purchases	$9,200 to $1,600 (2004 to 2006)[b]	$6,150 (2006)	$3,000 (2006)	$12,000
Energy	$4,867, $7,924, $2,576 (2004, 2005, 2006)	$2,600 (2005)	$4,200 (2006)	$4800 to $9600
Regular nitrate testing	$900	$450	$500	
Additional labor	$16,000 (2005). Manager estimates 60% to 65% of his time is spent on the treatment system.		$13,000	
Other operation and maintenance costs	$5,400 (for general upkeep)			$600 (maintenance parts)
Total extra costs of treatment[c]	$1.82 to $2.25 per 1000 gal.	$0.82 per 1000 gal.	$1.68 per 1000 gal.	$1.52 per 1000 gal.

[a] These are one time costs. Anion exchange systems are expected to last 20 to 25 years.
[b] Salt usage has gone down since a new well came on line in 2005.
[c] Includes construction costs amortized at 5% over 20 years. Does not include labor.

Distillation treatment system

Water is boiled and steam is condensed to yield water with very few dissolved substances. No Minnesota municipalities use distillation systems.

Well blending

Some Minnesota cities blend water from low and high nitrate wells to produce safe drinking water. At its simplest, blending is a matter of using low nitrate wells first and running the high nitrate wells last and only as needed. This involves minimal costs except labor and additional wear on the pumps in the wells being used most often. In some cities, blending has costs associated with managing pumps and testing water to ensure the final water is safe.

Blending is only an option if a city has wells with different nitrate concentrations that are pumped into a common area where the water can mix before going into the distribution system.

Annual costs of well blending include:

- Time associated with monitoring nitrate concentrations and switching pumps.

  $3,000 Melrose

- Frequent lab tests to monitor nitrate concentrations

  $1,000 Melrose
  $900 Clear Lake

Wellhead Protection

Wellhead protection is the process of managing potential sources of contamination within the capture area (wellhead protection area) for the well in an effort to reduce the risk of contamination at concentrations that present a human health concern. Wellhead protection plans consider potential sources of nitrate, industrial contaminants, and other potential contaminants. More information is available at the Minnesota Department of Health web site (see Resources). Compared to water treatment, wellhead protection is a more comprehensive and cost-effective response to the problem of aquifer contamination.

Wellhead protection plans (WHPPs)

Wellhead protection plans will eventually be required for all 954 community water systems and about 700 noncommunity (schools, factories, etc.) public water supply systems in Minnesota. About 130 of these systems have approved WHPPs and another 180 are preparing them. WHPPs describe the aquifer, capture zones (recharge zones for a well), current and future threats to groundwater quality, and detailed activities that will be undertaken to reduce or prevent contamination. They must be updated after ten years.

Costs of wellhead protection

Costs of wellhead protection planning and implementation are highly variable depending on each city's unique situation. This section describes potential expenses of protecting a water source.

Labor. The development of a wellhead protection plan is a joint effort between the city (or its contractor) and staff from the Minnesota Department of Health and the Minnesota Rural Water Association. After development of the WHPP, maintenance and implementation of the plan generally requires 5% to 10% of the time of a community water manager.

Some cities have hired people dedicated to WHP implementation. For example, the cities of Rockville, Richmond, and Cold Spring, and several Cold Spring private businesses have joined together to hire a non-staff member to implement their wellhead protection plans. In southwest Minnesota, a proposal is underway to hire a person to work within five counties to implement wellhead protection activities.

Implementation includes maintaining good communication with county officials and other local government units to ensure that decisions about zoning, licensing, and rules consider the effect on the wellhead protection area. Time also may be spent implementing educational efforts, promoting best management practices to land owners, and encouraging key owners to take advantage of cost share programs to take land out of agricultural production. .

Land purchases. Considering the cost of a water treatment plant and other approaches to wellhead protection, the city of Perham decided the most effective use of their money would be to purchase irrigated agricultural land within their wellhead protection zone. They began by buying land adjacent to the city, reselling some of it for residential development. They plan to gradually buy other land within the 10-year recharge zone and put it into conservation easements.

Cost share. Cities often encourage land owners to participate in federal and state programs that pay per-acre support to remove land from agricultural production. Some cities have provided additional financial incentives to land owners. Statewide in 2006, 20,283 of the acres in CRP, CREP2, and RIM were in wellhead protection areas. If land is enrolled in CRP for the purpose of wellhead protection, it must be within 2000 feet of the well. This has restricted the use of CRP. CREP2, on the other hand, does not have a radius limit.

Cities have also funded incentive programs to encourage upgrading of septic systems and sealing of unused wells.

Technical assistance is important to help landowners implement best management practices (BMPs) related to nutrient management, irrigation, manure management, turf management, and private well and septic system maintenance. This assistance is usually one-on-one work provided by partners including Soil and Water Conservation Districts, Watershed Districts, Minnesota Extension Service, Natural Resources Conservation Service, County Environmental Services Departments, Minnesota Department of Agriculture (MDA), and crop consultants. Additionally, the University of Minnesota and the MDA support research and demonstrations to test and illustrate the implementation of BMPs.

Education. All wellhead protection plans include education components to build awareness and knowledge. Especially important is providing opportunities for youth, such as children's water festivals and school programs. Other educational activities include posting road signs to mark the boundaries of the wellhead protection area, exhibits at county fairs and similar events, pamphlets, public service announcements, and direct mailings to people within the wellhead protection area. Educational resources such as bulletins and fact sheets are available from the MDA and Minnesota Rural Water Association.

Monitoring. Some cities have installed monitoring wells or organized a network of private wells to be tested regularly to monitor nitrate concentrations in the aquifer. The MDH spends $1500 to $2000 per year for mandatory quarterly testing of water supplies over 5.0 mg/L nitrate-N.

Cost examples

The following are examples of expenses associated with wellhead protection planning and implementation.

$15,000 to $40,000	**Melrose, WHP delineation paid by MDH**
$100,620	**Cold Spring, WHP plan development and groundwater quality studies funded by an MPCA Clean Water Partnership Grant**
$18,000	**Park Rapids, WHP plan development by the Hubbard County Water Plan**
$250/well	**Cold Spring, cost share to seal wells**
$300	**Cold Spring, education about well maintenance**
$250	**Cold Spring, education about septic systems**
$1,000	**Cold Spring, public education through various media, festivals and promotional items**
$800/yr	**Park Rapids, itemized annual costs**
$1,250	**Park Rapids, itemized one-time costs**
$4,000/yr	**Melrose, education**
$2,500/yr	**Melrose, consultant**
$6,000/yr	**Melrose, staff time**

Barriers to wellhead protection

City water managers identified the following barriers to effective wellhead protection, as it relates to nitrate contamination.

- **Uncertainty**. Hydrologists can predict the source of nitrate contamination and the path and timing of water movement from the surface to the aquifer, but they are rarely certain. Furthermore, in many places aquifer recharge occurs over decades. If it took years for nitrate concentrations to rise, it will likely take years for concentrations to decline in response to management changes. Expenditures can be difficult to justify when the benefit may not be expected for years and the magnitude of the benefit is uncertain.

- **Competing priorities**. Effective wellhead protection depends on long-term commitment from all decision-makers within the public water supplier, including water managers, city administrators, and city council members. Additionally, local and state officials, landowners, and the general public must be committed. All these stakeholders have competing concerns ranging from short-term budgetary issues to other natural resource concerns such as surface water programs. Attention will be turned to where funding is available.

- **Lack of authority**. The wellhead protection area for a well is often outside city boundaries. Public water suppliers have no authority to control land use beyond their jurisdictional boundaries. They depend on local zoning authority to manage proposed land-use changes and on state and county enforcement of rules governing septic systems, feedlots, and other nitrate sources. Most importantly, they often rely on voluntary cooperation from farmers and homeowners who apply fertilizer or manure.

- **Ineffective policies for administering conservation programs**. In some places, the best way to reduce nitrate contamination is to take a small amount of land in the wellhead protection area out of agricultural production. Federal cost share programs such as the Conservation Reserve Program (CRP) are designed primarily to protect soil and surface water and may not be as effective for wellhead protection. For example, the CRP provides per-acre incentives to take key land out of row crop production. Land within a 2,000-foot radius of a community well and within a wellhead protection area can be automatically enrolled in CRP. However, this reduces the number of possible acres because much of the land within 2,000 feet of the well may not actually be within its capture area. Using a fixed radius or other simple method to delineate a well water protection area can result in substantial over protection of land down gradient from the well and under protection of up-gradient land (Hodgson et al., 2006; Raymond et al. 2006). Another limitation of existing conservation programs is that incentive payments may not be adequate to allow farmers to take highly productive farmland out of production, especially as prices of corn and other commodities rise. Given the value of drinking water to human health, it may be appropriate to provide higher incentive payments to set aside land in wellhead protection areas that will protect aquifers from long term contamination.

- **Diverse and unequal stakeholders**. The costs and benefits of wellhead protection, and the power to influence land use and management are held unevenly by the city, township, county, state, residential water users, industrial water users, developers, farmers, homeowners, and other land owners. A successful solution requires communication and cooperation among all the parties and acknowledgment of the unevenness of costs and benefits. Out of fairness and expedience, planners may try to spread costs among many stakeholders by choosing wellhead protection activities that apply to everyone, such as promoting nutrient best management practices. Getting all players to contribute to the solution is essential, but may be inadequate where it is necessary to take a few key acres, owned by one or two producers, completely out of agricultural production. Working with producers to implement such "unfair" solutions is made more difficult by the uncertainty of the results.

- **Inertia**. Water suppliers may be hesitant to begin WHP planning and implementation – a task with an unknown time commitment. However, with the support of the Minnesota Department of Health (MDH) and the Minnesota Rural Water Association (MRWA), most have found the process to be manageable and successful.
- **Technical support is not a barrier.** All cities interviewed agreed they received good technical support from the MDH and MRWA. Every wellhead protection plan depended on extensive staff time from MDH and MRWA. Conservation Districts and the Minnesota Department of Agriculture have provided technical assistance with nutrient management planning.

The Bottom Line: How Much Does Water Cost?

The cost to supply water to a community varies greatly (Table 3). Costs for municipalities with treatment systems are several times higher than those without. Timely and effective wellhead protection can reduce or completely prevent nitrate treatment costs, as well as reduce the threat of other types of contamination.

Regardless of whether water is treated, consumers and taxpayers pay the costs of groundwater contamination – either in the form of increased water user fees, health effects, or impacts to the community's tax base. Taxpayers also pay the costs of groundwater protection, but these costs may be less than the costs of treating drinking water or finding clean alternative sources.

Table 3: Cost to supply water

City	Cost ($/1000 gal.)	Calculation
Anion exchange system		
Clear Lake	$7.23	Total water supply cost
Ellsworth	$4.55	Total water supply cost
No nitrate removal system		
Cold Spring	$1.40	User fee
Melrose	$1.15[a]	User fee
Park Rapids	$1.50	User fee, including sewer
Perham	$1 to $2	User fee

[a] Proposed iron treatment plant in Melrose would raise cost to $2.50 or $3.

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Glossary and Resources

Capture area – the subsurface area through which water is likely to move toward and reach a public water supply well.

Drinking water supply management area (DWSMA) – the MDH-approved surface and subsurface area surrounding a public water supply well that must be managed by the entity identified in a wellhead protection plan. The DWSMA completely contains the wellhead protection area but may be larger because its boundaries follow identifiable landmarks such as property and political boundaries.

Federal and state conservation programs – These programs for farmers can be used to support best management practices that protect wellheads. Contact the local Soil and Water Conservation District for more information.

Environmental Quality Incentives Program (EQIP)
Conservation Reserve Program (CRP) – a federally funded program in which farmers are paid to take land out of agricultural production for 10 to 15 years. Payments generally match local rental rates.
Conservation Security Program (CSP)
Conservation Reserve Enhancement Program (CREP2) – a state-funded program similar to CRP.
Reinvest in Minnesota (RIM) – a state-funded program.

MDA – Minnesota Department of Agriculture
http://www.mda.state.mn.us/protecting/waterprotection/drinkingwater.htm

MDH – Minnesota Department of Health supports wellhead protection planning and monitors nitrate concentrations in public water supplies.
Source Water Protection page: www.health.state.mn.us/divs/eh/water/swp/index.htm.

MPCA – Minnesota Pollution Control Agency
Ground Water in Minnesota: http://www.pca.state.mn.us/water/groundwater/
Clean Water Partnership Program provides grants and loans to address surface and groundwater pollution problems: http://www.pca.state.mn.us/water/cwp-319.html

MRWA – Minnesota Rural Water Association supports wellhead protection planning. Their work is supported by rural water suppliers and taxpayers. Look to their web site for educational materials and guidance documents. www.mrwa.com/sourcewater.htm

ppm – parts per million. PPM is equal to milligrams per liter (mg/L) when measuring the concentration of a substance in water.

Recharge area – the surface and subsurface area that provides water to an aquifer (although sometimes the term is used to refer to the area that supplies a well).

Reinvest in Minnesota (RIM) – a state-funded program that builds on CREP2 by adding a conservation easement that is either permanent or adds 30 years beyond the CREP2 contract.

Wellhead protection area (WHP area) – the designated area around a public water supply well(s) that is to be protected from contaminants that may adversely affect human health. It includes the surface and subsurface area through which contaminants are reasonably likely to move toward and reach the well(s). Regulation of WHP areas was established under the federal Safe Drinking Water Act, and is implemented through state governments.

SURVEY OF WELL OWNERS ABOUT DRINKING WATER QUALITY

This survey was mailed to 800 private well owners in the central sand plains of Minnesota in the summer of 2006. For further information see: www.mda.state.mn.us/protecting/waterprotection/drinkingwater.htm or A.M. Lewandowski, B.R. Montgomery, C.J. Rosen, and J.F. Moncrief. 2008. Groundwater nitrate contamination costs: A survey of private well owners. Journal of Soil and Water Conservation (forthcoming).

Annotations are underlined and italicized, and are provided as suggestions for future surveys.

*Please answer the following questions about **property you own with a private drinking water well** (which may be at a different address than where this survey was mailed). Circle the number or letter that corresponds to the answer closest to your opinion, or write in the information requested. All individual responses will be kept strictly confidential. As a way of saying thank you, we will send you a **FREE NITRATE TEST KIT** worth up to $20 once we receive your completed survey.*

Q1. In which Minnesota county and township is your property which has a private drinking water well? ***All questions refer to this same property***.
______________________________ County
______________________________ Township

Q2. How many wells are used at this residence? _________ Wells
We asked this question so the note before question 4 would make sense about which well to use. 92% had one well, 6% had two, and a few had three or four.

Q3. Where does the **DRINKING** water come from for this property? (*Circle one*.)

1. Private well ➔ **CONTINUE WITH Q4**
2. Public or municipal supply ➔ **SKIP TO Q13 ON PAGE 3**
3. Community, non-municipal supply (e.g., a trailer park or apartment complex outside the municipal water system) ➔ **SKIP TO Q13 ON PAGE 3**
4. Don't know ➔ **SKIP TO Q13 ON PAGE 3**

The purpose of this question was to weed out any people on municipal water supplies that slipped through our sample selection process.
Consider adding a separate question asking if they drink their well water. Based on comments in other parts of the survey, it became clear that some people drink bottled water or bring water from their primary residence to drink instead of their well water. Many probably do this for reasons other than nitrates. (See Q16.)

NOTE: If more than one well is used at this property, please answer the following questions for the ONE well that supplies most of the drinking water.

Q4. Where is this well located? (*Circle all that apply*.)

a. In town or the outskirts of town
b. At your second home or recreational residence
c. Farm (either active or retired)
d. Rural area but <u>not</u> a farm

e. Trailer court

f. Other (*Please specify*) ________________________________

This question was not very usefulness. It would be better to focus on Q5. It might be fruitful to ask how much land people own, and therefore control, around the well.

Q5. What is the **PRINCIPAL** land use within ¼ mile of your well? (*Circle one*.)

1. Cropland
2. Pasture or grassland
3. Forest
4. Lawn
5. Other (*Please specify*) ________________________________

We got far too many "others" – 100 of the 483 respondents. These included 44 mixed uses, 27 residential lots of various sizes (or maybe just their own residence), and 23 water bodies including wetlands, streams, and lake fronts. Also, 1 "lawn and road", 2 golf courses, and 1 gravel pit.

Q6. How is your well constructed? (*Circle one*.)

1. Drilled
2. Driven or sand point
3. Dug or augured
4. Other (*please specify*) ________________________________
5. Don't know

We got no "others".

Q7. How old is your well? (*Circle one*.)

1. Less than 15 years
2. 15 – 30 years
3. More than 30 years old
4. Don't know

Q8. How deep is your well? (*Circle one*.)

1. Less than 50 feet
2. 51 – 100 feet
3. 101 – 300 feet
4. More than 300 feet
5. Don't know

Q9. What is the width of the well pipe? (*Circle one*.)

1. Two inches or less
2. Greater than two inches
3. Don't know

Delete this question. We asked it to double-check the well type, but more people knew their well type (88%) than knew the width of the well pipe (75%). Of those with drilled wells, 13% said the pipe was <2" and 27% said >2". Of those with sand points, 79% said <2" and 6% said >2".

Q10. A County Well Index Number (CWI), or a Minnesota Unique Well Number, is a six-digit number assigned to wells installed since 1974. This number may be on an aluminum tag attached to the outside of the well casing. The CWI will help us to determine the geology of your well. More information is available at: http://www.health.state.mn.us/divs/eh/cwi.

Does your well have a County Well Index Number? (*Circle one*.)

1. Yes ➔ | If you know it, what is the County Well Index Number? ______________________________
2. No
3. Don't know

Q11. When was your **DRINKING** well water last tested for nitrates? (*Circle one*.)

1. Never
2. Within the past year ➔ **(PLEASE SKIP TO Q12)**
3. Within the last 3 years ➔ **(PLEASE SKIP TO Q12)**
4. 4 - 10 years ago
5. More than 10 years ago
6. Don't know

Q11a. If you do not test your water at least every 3 years, please indicate why not: (*Circle all that apply*.)

a. Don't feel a need to have it tested *(Please explain)* ________________
b. I don't know how to test my water
c. It costs too much
d. It is not convenient
e. The water is probably fine *Delete this option. It is a subset of the first.*
f. Have not had time
g. Other (Please specify) ______________________________

(PLEASE SKIP TO Q13)

Q12. If you tested your **DRINKING** well water for nitrates within the last 3 years, what were the results of the test? Enter a value if you know it **OR** circle one answer.

__________ ppm (parts per million)

1. Safe drinking water (less than 10 ppm)
2. Above the safe drinking water standard (above 10 ppm)
3. Don't know

Q13. The U.S. Environmental Protection Agency (EPA) says that nitrate levels of greater than 10 ppm (parts per million) in drinking water are unsafe, especially for infants and the elderly.

At what nitrate level would you begin treating your water or finding an alternative source of drinking water? (*Circle one*.)

1. Before drinking water nitrate levels reached 10 ppm
2. When nitrate levels reach 10 ppm
3. After nitrate levels had risen above 10 ppm

Q14. Do you currently **own** a treatment system to remove nitrate from your drinking water? (Do not include water softeners or iron removal systems, unless they were acquired to improve the performance of the nitrate treatment system.)

1. Yes ➔ | What type of treatment system do you own? (*Circle one*.)
2. No

1. Reverse osmosis
2. Distiller

3. Anion exchange
4. Other (*Please specify*) ________________________________

What was the initial cost of your system? $__________________

What is the annual maintenance cost? $____________________

Q15. Do you currently **lease** a treatment system to remove nitrate from your drinking water? (Do not include water softeners or iron removal systems, unless they were acquired to improve the performance of the nitrate treatment system.)

1. Yes ➔
2. No

What type of treatment system do you lease? (*Circle one*.)

1. Reverse osmosis
2. Distiller
3. Anion exchange
4. Other (*Please specify*) ________________________________

What was the initial cost of your system? $__________________

What is the annual cost? $____________________

Consider combining 14 and 15 into the following:

Do you currently own or lease a treatment system to remove nitrate from your drinking water? (Do not include water softeners or iron removal systems, unless they were acquired to improve the performance of the nitrate treatment system.)

1. Own ➔
2. Lease ➔
3. Neither own nor lease

What type of treatment system do you own or lease? (Circle one.)

1. Reverse osmosis
2. Distiller
3. Anion exchange
4. Other (Please specify) ________________________________

What was the initial cost of your system? $__________________

What is the annual maintenance cost? $____________________

Q16. Do you ever drink **bottled** water because of *concerns about* elevated nitrate levels in your well water?

1. Yes ➔
2. No

About how much do you spend on bottled water each month?

$____________________

Consider this:

What is your primary source of drinking water?

*1. The well described in this survey ➔ **SKIP TO Q17***
2. Bottled water ➔

About how much do you spend on water purchases each month?

$ ____________________

3. Municipal tap water
4. Another well
5. Other (Please specify) ____________________

If you don't drink your well water, why not? (Circle all that apply.)

a. Concerns about nitrates
b. Concerns about other contaminants (please specify) ____________
c. Flavor or odor
d. Don't know
e. Other (please specify) ____________________

Q17. Have you installed a new well **because of elevated nitrate levels in your water**?

1. Yes ➔ What was the approximate installation cost for your new well?

   $______________________

2. No

Consider asking when the well was installed. It may make a difference if it was recent or many years ago. Also decide whether you want to these people to answer other questions with regard to their new well or old well. For example, for our survey they described their new well as being low in nitrate, but for analyzing people's actions, we wanted to include them in the high-nitrate group because their nitrate was high before they took the action of installing the well.

Q18. Are there any other things you have done because of elevated nitrate levels in your drinking water?

1. Yes ➔ Please describe what you have done and the costs:
2. No

Q19. Treatment systems commonly cost $500 to over $1000 to install, plus $60 to $100 per year for maintenance.

If the nitrate levels in your well water became too high to have safe drinking water, would you purchase or lease a treatment system (if you haven't already done so)? (*Circle one*.)

1. Yes ➔ What type would you purchase or lease? (*Circle one*.)
   1. Reverse osmosis
   2. Distiller
   3. Anion exchange
   4. Other (*Please specify*) ______________________
   5. Don't know
2. No
3. As indicated in Q14 or Q15, I already have a treatment system.

Q20. If you decided **NOT** to purchase or lease a treatment system, what **OTHER** action would you be most likely to take in response to elevated nitrate levels? (*Circle one*.)

1. Drink bottled water (*Commonly $0.30 to $1.35/gal, or $100 to $500/person/year.*)
2. Install a new well (*Commonly $5000, or much more if drilling into bedrock*.)
3. Move to a new residence
4. Other (*Please specify*) ______________________________

5. Would not do anything

Consider combining questions 19 and 20. We separated them to allow us to ask what kind of treatment system they would purchase. But that is not important to ask, because they do not know. It made it difficult to statistically combine the results of the two questions.
*Also, people are likely to drink bottled water first and then take one of the other actions, so some people listed both. It might be better to ask what **long term** action they would take.*

Q21. How concerned are you about the following water quality issues related to your **DRINKING WATER**? (*Circle one answer for each item*.)

		Very Concerned	Somewhat Concerned	Not Very Concerned	Not At All Concerned
a.	Nitrate contamination	1	2	3	4
b.	Bacterial contamination	1	2	3	4
c.	Contamination with herbicides, volatile organic compounds, or other chemicals	1	2	3	4
d.	Iron or other minerals	1	2	3	4
e.	Taste, odor, or color	1	2	3	4

Another way to ask would be "Are you aware of the following water quality problems in your county?"

Q22. To what extent do you agree or disagree with the following statements? (*Circle one answer for each statement*.)

		Strongly Agree	Agree	Disagree	Strongly Disagree	Don't Know
a.	I have ample opportunities to learn about the quality of my water.	1	2	3	4	5
b.	Federal, state, and local governments are doing an adequate job protecting groundwater in my community.	1	2	3	4	5
c.	Poor drinking water quality has reduced property values in my COUNTY.	1	2	3	4	5

Q23. Do you believe that elevated nitrate levels have reduced the value of **YOUR** property? (*Circle one*.)

1. Yes ➔
2. No
3. Don't know

About how much has your property value been reduced?

$______________________

Q24. During the past 10 years, has the drinking water from **YOUR** well improved in quality, stayed about the same, or decreased in quality? (*Circle one*.)

1. Improved in quality
2. Stayed about the same
3. Decreased in quality
4. Don't know

Q25. During the past 10 years, has the drinking water in your **COUNTY** improved in quality, stayed about the same, or decreased in quality? (*Circle one*.)

1. Improved in quality
2. Stayed about the same
3. Decreased in quality
4. Don't know

THANK YOU VERY MUCH FOR HELPING WITH THE SURVEY.

Please return your survey in the postage-paid envelope provided to:

Minnesota Center for Survey Research
University of Minnesota
1313 Fifth Street SE, Suite 108
Minneapolis, MN 55414-4533

Minnesota Phosphorus Source Assessment Tool

Based on the CWP Watershed Treatment Model

User Guide

and

Documentation

July 10, 2007

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Support for this project was provided in 2005 by the Environment and Natural Resources Trust Fund as recommended by the Legislative Commission on Minnesota Resources.

What is the Phosphorus Source Assessment Tool?

The Minnesota Phosphorus Source Assessment Tool (PSAT) is an Excel-based tool used at the watershed scale to identify the relative contribution of sources of P to a lake or stream. It is a modification of the Watershed Treatment Model. (See www.cwp.org for more information about the WTM).

The PSAT has two main applications: education and initial watershed assessments or screenings.

Education. PSAT identifies and illustrates the relative contribution of most P sources. This helps watershed planners explain the sources of phosphorus and how the sources are affected by changes in land use and land management. Teachers can use PSAT to increase awareness of watershed issues and discuss the application of models to environmental planning.

Initial assessment. PSAT does not require specialized software or training, so it is suitable for an initial screening to identify phosphorus sources in a watershed. Results from PSAT will help clarify which additional models or data collection are needed to adequately understand a watershed to support decision making and planning.

How PSAT relates to other tools. Estimating sources of phosphorus is an inexact science. The PSAT is meant to be one of several pieces of evidence used to understand phosphorus movement in a watershed.

Benefits and limitations. The advantages of PSAT are that it addresses a comprehensive list of P sources and does not require specialized software or training. The major disadvantages are that it only provides relative P amounts, not actual P loads, and the simplified calculations may provide misleading results if not interpreted correctly. The main barrier to use is the need for land use data, but such data will be needed for any analysis of phosphorus sources.

Where can PSAT be used?

PSAT is suitable for assessing lakesheds or river watersheds.

Watershed size. PSAT is intended for small to medium-sized watersheds. Loading factors for rural areas are based on data from watersheds less than 200 sq miles, so the PSAT should not be applied to larger watersheds. In urban watersheds (more than 30% urban development), the maximum watershed size should be limited to 20 square miles. This is because the urban runoff estimate is based on the Simple Method, which was originally designed for development lots less than 1 mile square.

TMDL studies. The PSAT may be more useful during for the implementation stage than for setting TMDLs. Despite the conservative assumptions in the PSAT, it may be necessary to assign an explicit margin of safety when a specific target needs to be met. The PSAT is not a calibrated model, so relative change in P loading should be used rather than the absolute loading values. The PSAT generates annual loads, so it cannot account for critical conditions that occur during the year.

How to use PSAT

1. Gather inputs. Gather the inputs needed to run the model. Information about each input is available below, and a list of all necessary inputs is in the data collection sheet available on the web site (http://www.mnpi.umn.edu/psat.htm). Sources of input data are described starting on page 12. The quality of results depends on the quality of inputs. Document all the assumptions and uncertainties related to the inputs.

2. Enter data for multiple scenarios. After you gather your input data, enter it into the Excel spreadsheet. Your inputs will include some uncertainties and the assumptions made by the tool have some uncertainty. Show the impact of uncertainty by running the tool a few times using different input assumptions.

3. Use PSAT to generate questions. Compare results from scenarios that represent the high and low possible input values. This will help you identify other models or data needed to improve understanding of the watershed. For example, results from multiple scenarios might show that you need to gather information about the condition of septic tanks or run a more detailed model of the effect of agricultural practices.

4. Use PSAT to educate. Graphs from the model can be used to explain P sources to stakeholders.

A Tour of the Excel File

Color of cells

Green cells need to be completed by the user
Blue cells have default or calculated values but may be substituted
Grey cells should not be changed
Purple Cells Reflect "Bottom Line" Loads or Load Reductions

Worksheets

The Excel file consists of several worksheets. You can switch among the worksheets by clicking on the tabs at the bottom of the window. You sill mainly focus on the green tabs: Primary Sources, Secondary Sources, and Results. Here is a description of each of the worksheets:

	Worksheet name	Purpose
The main load calculation sheets	Primary Sources	Enter land use data.
	Secondary Sources	Enter data about other P sources, such as septic systems, permitted discharges, and feedlots.
	Results	View results of load calculations.
Calculate load reductions from current management practices	Existing Management Practices	Enter data about practices that can reduce loading, such as catch basins or septic system education.
	Discounts – Existing	
	Existing Loads	
Estimate P load changes with changes in land use and management practices.	Future Management Practices	
	Discounts – Future	
	Future Land Use	
	New Development	For data about developments, such as the number of households with septic systems.
	Loads with Future Practices	
	Loads Including Growth	
Information	Data sources	Suggestions for data inputs
	Summary Sheet	
	WTM user guide	User guide that came with the original model on which the PSAT is based.

Entering Data

Input data goes into the green cells. Not all green cells need to be completed – only those that relate to P sources found in your watershed.

The blue cells are default or calculated values that can be left as is, or can be changed to better match local conditions. The default values are typical for central Minnesota, but actual values may vary substantially. The quality of results can be improved by using values that fit local conditions. For example, you may want to change the P loading rates in cells H36-H41 if farming practices in the watershed are higher or lower risk than in average watersheds. For instructions, see “Adjusting agricultural loading factors” on page 14.

Primary Sources Worksheet

Watershed data

Enter average **annual rainfall** for the watershed. (See “Data Sources” worksheet for a rainfall map.)

Watershed area will be summed automatically.

Stream length of all streams within the watershed is only used in the estimate of channel erosion.

Planning horizon is only used in the Future Management Practices worksheet, so most users can leave this blank.

Land use acres

Enter number of acres of each land use within the watershed. If desired, add labels in Column C. If the land use distribution is uncertain, determine a range of possibilities. Then, run the tool for two or more possible land use distributions to learn the range of potential P sources. See page 12 for suggestions for acquiring land use data.

Residential

LDR, MDR, and HDR stands for low-, medium- and high-density residential. The only difference among these is the percentage impervious cover (Column E). You can change these default impervious cover values if you have local data.

If residential lots are larger than 2 acres or less than 10% impervious cover, list them as “rural development” in Row 35.

Impervious cover includes any hard surfaces where rain water cannot infiltrate, i.e., roofs, any paved surfaces, and gravel roadways.

Commercial and Industrial

When deciding whether land should be categorized as commercial or industrial, the main distinction is the percent impervious cover (column E). A distinction between the two categories is not defined in the original WTM documentation (See References on page 21).

Urban Roadways

“Urban roadways” includes the right-of-way.

Rural roads should not be included in “urban roadways” because they are accounted for in the loading factors for agricultural and forest lands.

If your data source separates rural road acres from other rural land cover, you can create a separate rural road category on one of the blank lines. Use a P loading factor of 0.1 to 0.2 (column H), depending how well road runoff is connected to surface water. For example, if a road ditch has water in it for much of the year, then most of the P that reaches the ditch will eventually be carried to surface water, and the loading factor should be 0.2. If little of the runoff is likely to reach surface water, use a loading factor of 0.1. (The two sources of P from roads are atmospheric deposition at 0.2 lbs/ac and road sanding, which is handled under secondary sources.)

Forest, brush, or grassland

Include any land where the soil is generally undisturbed and uncompacted. Infiltration is much higher on these lands than any others.

Gravel pits and other large open mines can be ignored because of their small area. If they constitute a significant proportion of the watershed, the acres should not be included in the total acres in the watershed on the assumption that no runoff is generated from them. If the mines generate runoff, consider including the acreage in “Active construction”.

Rural development

"Rural development" refers to housing on lots that are 2 acres or larger, or less than 10% impervious cover. Farm home sites can be included in this category or as part of agricultural acreage.

Agriculture

If possible, divide agricultural land acreage into row crops with manure applications, row crops without manure applications, and pasture/perennials. If that level of detail is not available, put all agricultural land into the category of "mixed agriculture", or into "dairy" if dairy is the primary ag system in the watershed. "Mixed agriculture" is an average of the factors used for "Row crop ag" and "Pasture, perennial ag". "Dairy" is based on a rotation of 2 years corn with manure applications followed by 3 years alfalfa.

The agricultural loading factors in column H can be adjusted to better reflect practices in the watershed by using the Minnesota Phosphorus Index to assess P loss risk. See "Adjusting agricultural loading factors" on page 14 for instructions.

Open water

Enter the surface area of the lake whose watershed is being studied in the category of "Lake or river of interest". Other lakes and open water wetlands should be included as "Upstream open water". Wetlands without open water can be included in "Forest, brush, or grassland.

The P loading factor for the lake of interest represents atmospheric deposition of P. Of the atmospheric P that lands on upstream water bodies, not all will be transported to the end of the watershed.

Active construction

Estimate the average number of acres at any point in time that is under construction or otherwise exposed to severe sediment losses.

Highly erosive unpaved drives may be included as "Active construction".

Vacant lots

This category is meant for mostly unvegetated urban lots.

Secondary Sources Worksheet

Dwellings or population

The number of dwelling units and the total population are used in calculations of loading from septic and sewer systems. Enter either the number of dwellings or population and the program will calculate the other value based on the number of individuals per dwelling (Cell E3).

If some people are seasonal residents, reduce the number of dwellings or population proportionately.

To account for waste from commercial properties use the following conversions: For motels or other lodging, add 1 dwelling unit for every 4 guests (average daily occupancy). For restaurants, add 1 dwelling unit for every 8 seats. For other types of commercial operations, see the Metropolitan Council Environmental Services (2003).

Soil phosphorus

The surface soil total P is only used in the calculation of P load from active construction. The subsoil total P is only used in the calculation of P load from channel erosion. Use the equation and map on page 12 to estimate the percent total P in surface and subsurface soil.

Septic systems

Enter the proportion of dwellings on septic systems.

Check the default values in E17, G17, and I17 which indicate the proportion of systems that are compliant, failing, or an imminent threat to public health and safety (ITPHS). The defaults are average values for central Minnesota, but your county or watershed could be quite different. ITPHS systems include direct discharge to surface water or to the ground surface. Failing systems are those with obvious leaks or with less than the required vertical separation above the seasonal water table.

SSOs and Illicit Connections

These two sections relate to sewer systems. Use local data as much as possible. Avoid using the default values.

Channel erosion

Choose one of two methods to estimate channel erosion, or enter an estimate from an alternative model into the cell labeled “Bank Erosion Rate (tons/mi/yr):

Method 1 requires that you enter a measurement of the total sediment load going into the lake, or the load leaving the watershed. PSAT will subtract all runoff sediment sources and assume the remainder is from channel erosion.

Method 2 is only appropriate for use in primarily urban watersheds (>10% impervious cover). It assumes that changes in impervious cover cause a predictable enlargement in the stream’s cross-sectional area and estimates the amount of annual channel erosion that would be required to reach that enlarged area.

Livestock on open lots

Estimate the number of animals in confined areas exposed to rainfall runoff. Do not include animals kept in covered barns or on pasture. (Pasture should be included as agricultural land in the Primary Sources worksheet.) For “% Exposed to Runoff”, estimate the percent of time that the animals are in the confined area exposed to rainfall runoff.

Geese

If large numbers of geese defecate near your lake, you may want to include an estimate of their P contribution. On the other hand, geese generally defecate near what they eat, so goose feces may only represent a change in the form of P and not a net P input to the lake.

Marine toilets and recreation

Use this section to account for human waste dumped directly into the lake, such as from marine toilets that are not properly pumped out or from waste associated with fishing derbies or ice fishing.

The tool provides two methods for estimating this P source. You can use either or both, depending on the activities in your watershed.

For method A, enter the number of people that are on a boat for a full 8-hour day multiplied by the number of days. The calculation assumes all waste for the 8-hour day on the lake ends up in the lake. Proper dumping of waste can be accounted for in the "Existing Management Practices" worksheet in the Marina Pumpouts or Portable Toilets section. Alternatively, the flow rate (Cell E60) can be reduced proportionately.

To estimate the number of people-days for boats with marine toilets, multiply the number of boats by two people/boat by the number of days in the boating season by 50%. This is based on the WTM estimates that boats are occupied up to 50% of the boating season and two people per boat.

Use method B for ice fishing. Enter the number of ice houses or other clusters of fishing holes on the lake multiplied by the number of weeks in the ice fishing season. This calculation is based on a single study at Granite Lake which counted an average of 3.8 urine spots per week around each fishing site. The calculation assumes 0.25 mg (0.00055 lb) P per urine spot.

Road sanding

The road sanding section only needs to be completed if the sand contains phosphorus. A "closed section road" is one with a curb.

Permitted dischargers

Fill in data from NPDES permits for wastewater treatment plants or other permitted dischargers.

If you have measured P loads in the outflow from a water body within the watershed, this can be entered as a point source in this section. In this case, the subwatershed drained by the measured outflow must be removed from the primary land use categories. This could complicate estimates of future loads based on land use changes and management practices. It may be necessary to estimate changes in the subwatershed separately from the remainder of the area.

Existing and Future Management Practices

The "Existing Management Practices" worksheet allows you to estimate P load reductions below the general loads assumed in the "Primary" and "Secondary Sources" worksheets. Most of the practices on this worksheet relate to urbanized or impervious areas.

The "Discounts-Existing" and "Discounts-Future" worksheets show the proportion of P load reductions expected from each practice. "T" in column C indicates the treatability, i.e., the proportion of acres that are treated with a practice or the proportion of a population that can be reached. "D" in columns D to F indicate discount factors or effectiveness factors. These account for the fact that practices do not perform at 100% of their potential. For example, not all people reached by an education program will change their behavior, and not all the P or sediment will be removed by a sediment basin or buffer.

See the documentation for the Watershed Treatment Model (www.cwp.org) for more information about these worksheets.

Viewing Results

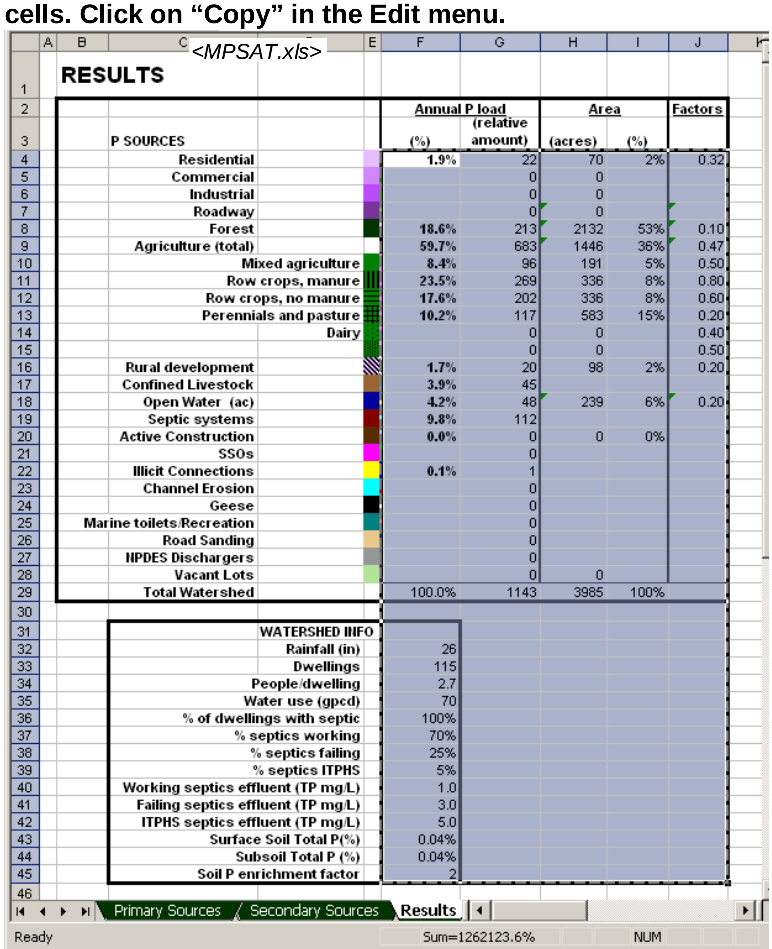
As soon as you fill in data on the Primary and Secondary Sources worksheets, loading calculations will appear on the Results worksheet. Two pie charts will be displayed – one showing the distribution of land use and the other showing the contribution of various sources of P to the end of the watershed. The table of annual P loads deliberately does not indicate the units. The PSAT should only be used to assess relative contributions, not actual P loads.

Because of uncertainty about inputs and default parameters in PSAT, the results pie chart should never stand alone. Ideally it should be displayed with one or more other graphs that illustrate the range of possible values for the watershed.

The MPSAT comparison graph file. To create bar graphs comparing alternative scenarios, use the Excel file <MPSATcomparisongraph.xls> available on the PSAT web site (www.mnpi.umn.edu/psat). To use the file,

1. Open <MPSATcomparisongraph.xls>
2. Go back to the PSAT "Results" worksheet. Copy the data within the dotted lines (Figure 1).
3. Switch to <MPSATcomparisongraph.xls>. Use "Paste special" from the edit menu to paste only the values starting in cell F8 (Figure 2).
4. Repeat steps 2 and 3 for another scenario for the watershed. This time, paste values starting in cell K8. There is room to paste six sets of data.
5. Add chart labels to row 5.
6. View "Comparison Chart" worksheet. (Figure 3)

Figure 1. To graph the results, first select the highlighted cells. Click on "Copy" in the Edit menu.



	P SOURCES	Annual P load (%)	Annual P load (relative amount)	Area (acres)	Area (%)	Factors
4	Residential	1.9%	22	70	2%	0.32
5	Commercial		0	0		
6	Industrial		0	0		
7	Roadway		0	0		
8	Forest	18.6%	213	2132	53%	0.10
9	Agriculture (total)	59.7%	683	1446	36%	0.47
10	Mixed agriculture	8.4%	96	191	5%	0.50
11	Row crops, manure	23.5%	269	336	8%	0.80
12	Row crops, no manure	17.6%	202	336	8%	0.60
13	Perennials and pasture	10.2%	117	583	15%	0.20
14	Dairy		0	0		0.40
15			0	0		0.50
16	Rural development	1.7%	20	98	2%	0.20
17	Confined Livestock	3.9%	45			
18	Open Water (ac)	4.2%	48	239	6%	0.20
19	Septic systems	9.8%	112			
20	Active Construction	0.0%	0	0	0%	
21	SSOs		0			
22	Illicit Connections	0.1%	1			
23	Channel Erosion		0			
24	Geese		0			
25	Marine toilets/Recreation		0			
26	Road Sanding		0			
27	NPDES Dischargers		0			
28	Vacant Lots		0	0		
29	Total Watershed	100.0%	1143	3985	100%	

	WATERSHED INFO	
32	Rainfall (in)	26
33	Dwellings	115
34	People/dwelling	2.7
35	Water use (gpcd)	70
36	% of dwellings with septic	100%
37	% septics working	70%
38	% septics failing	25%
39	% septics ITPHS	5%
40	Working septics effluent (TP mg/L)	1.0
41	Failing septics effluent (TP mg/L)	3.0
42	ITPHS septics effluent (TP mg/L)	5.0
43	Surface Soil Total P(%)	0.04%
44	Subsoil Total P (%)	0.04%
45	Soil P enrichment factor	2

Figure 2. Use the “Paste Special” command (Edit menu) to paste just the values into Cell F8 or K8 or P8, etc.

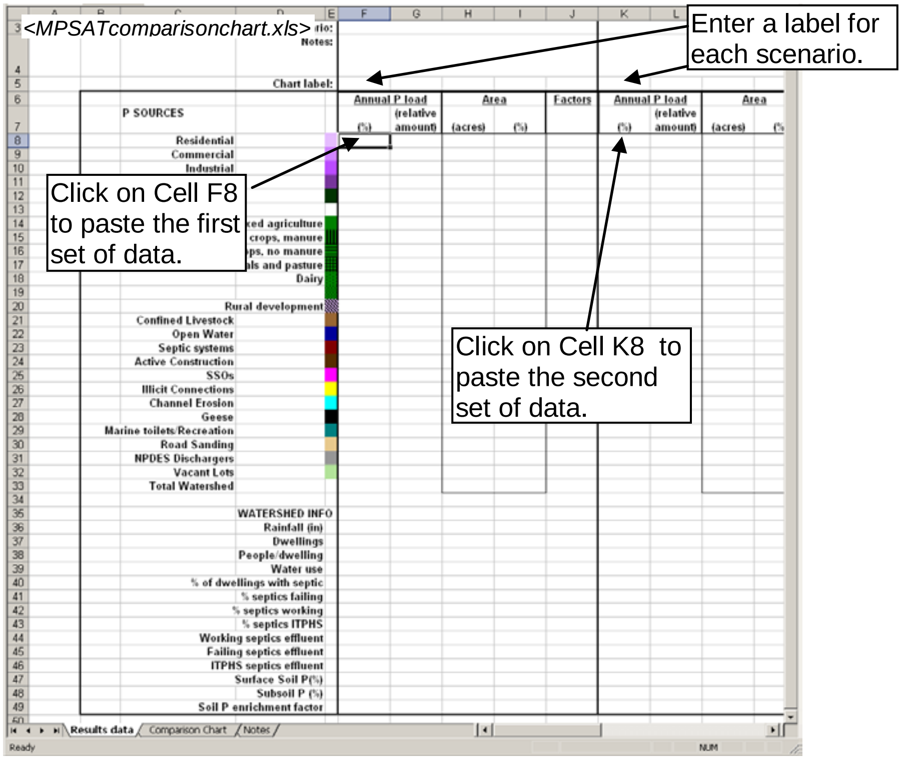
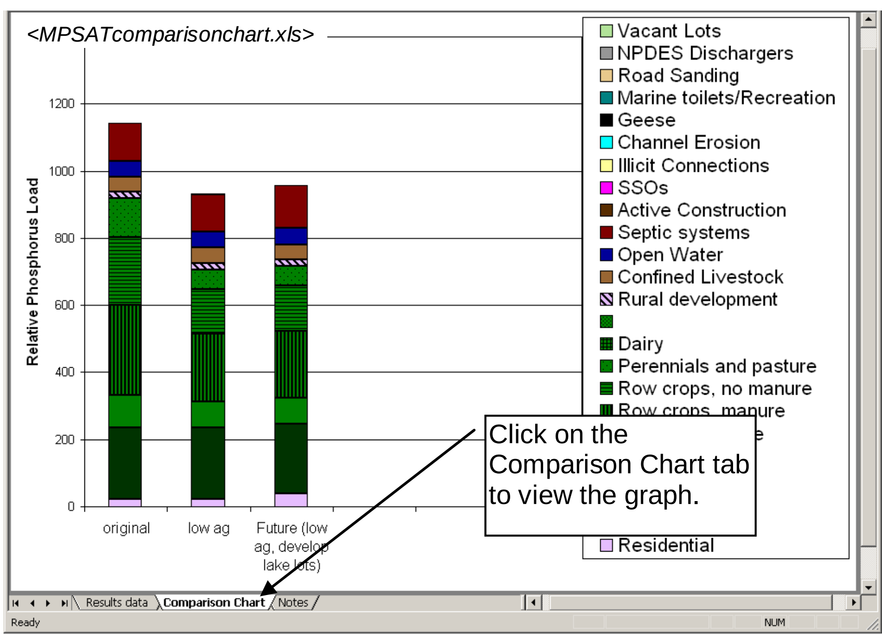
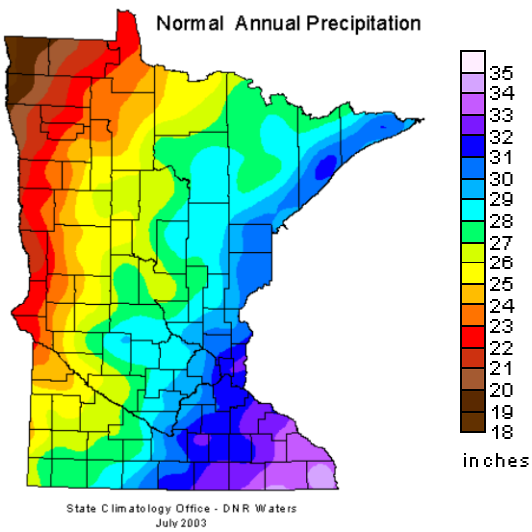


Figure 3. Data will be graphed in the Comparison Chart worksheet.



Sources of Input Data

Rainfall



Land use

Determining acreages involves defining the boundaries of your lake shed, determining land uses, and summing up the acres of each land use. Land cover and land use information may be available from a local planning agency such as:

- City zoning department,
- County Planning and Zoning, Environmental Services, or Information Services,
- Watershed District,
- Soil and Water Conservation District.

The Land Management Information Center (LMIC) has a table comparing several sources of land cover data at http://www.lmic.state.mn.us/chouse/land_use_comparison.html.

Land use data is available from the Land Management Information Center www.lmic.state.mn.us/chouse/land_use.html,
the DNR http://deli.dnr.state.mn.us/data_catalog.html,
and MetroGIS www.datafinder.org/index.asp.

Soil phosphorus

Surface soil P. Convert agronomic soil tests to percent soil phosphorus using the following equations:

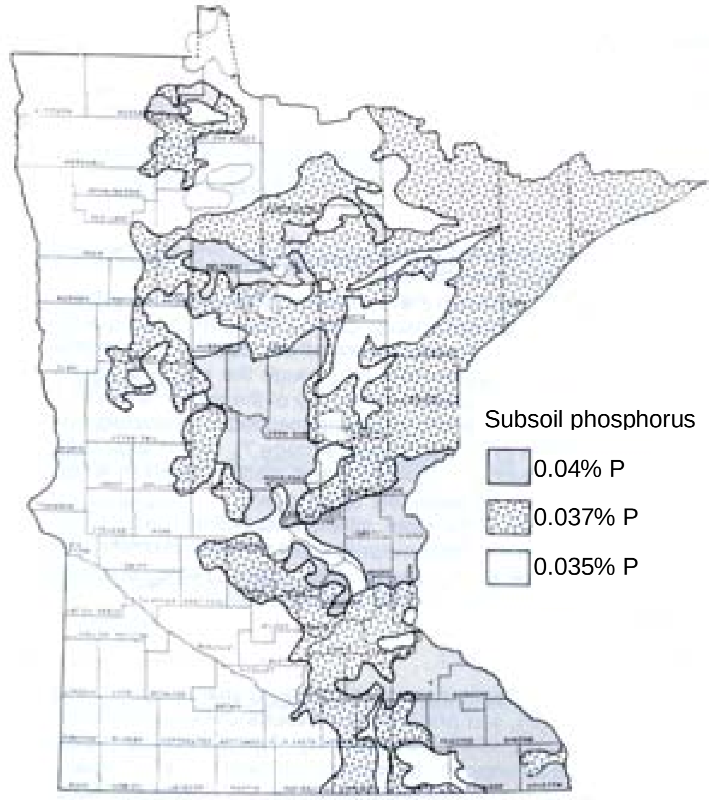
% P in soil = [321.9 + (2.785 X Olsen) + (29.11 X %OM)] / 10,000

Olsen-P ppm = 0.65 X Mehlich-P ppm

Olsen-P ppm = 0.71 X Bray-P ppm

These calculations will be done automatically in a table on the “Data Sources” worksheet in PSAT.

Subsoil P. Use the map below to estimate subsoil P.



Septic systems

Many counties estimate the proportion of failing septic systems. The Minnesota Pollution Control Agency provides state summaries of these estimates at http://www.pca.state.mn.us/programs/ists/localgovernment.html#annualreports. Request county level data from a county Environmental Services Department or by calling the MPCA (1-800-657-3864). Ask lake associations if any septic system surveys have been done in the watershed.

Geese

Examples of how people count geese are in:

Cooper, J.A. 2006. 2006 Program Report. The Canada Goose Program. Page 24 of http://www.ci.roseville.mn.us/council/parks/packets/2006/061205.pdf

Cordts, Steve. 2005. The 2005 Minnesota Waterfowl Breeding Population Survey. Wetland Wildlife Populations & Research. http://files.dnr.state.mn.us/publications/wildlife/populationstatus2005/migratorybirds.pdf

Manny, B.A., W.C. Johnson, and R.G. Wetzel. 1994. Nutrient additions by waterfowl to lakes and reservoirs: Predicting their effects on productivity and water quality. Hydrobiologia. 279/280:121-132.

Scherer, N.M., H.L. Gibbons, K.B. Stoops and M. Muller. 1995. Nutrient loading of an urban lake by bird feces. Lake Reserv. Manage. 11(4): 317-327.

Road sanding

Contact the county highway department for information about the P content and quantity of sand applied to roads.

Permitted Dischargers

Data about National Pollutant Discharge Elimination System (NPDES) permitees is public and available from the Minnesota Pollution Control Agency (MPCA), but you may have to ask for help to acquire and interpret the numbers. Start with discharge data from the MPCA Environmental Data Access site at: http://www.pca.state.mn.us/data/eda/. Look for the discharge limits listed in the source's NPDES permit, additional emergency discharges, and data from the Discharge Monitoring Reports (DMR), which all permitees must submit.

Adjusting agricultural loading factors

At a watershed scale, agricultural land generally delivers less than 1 lb P/ac/yr to the end of the watershed. However, values measured in Midwestern watersheds vary from near zero to 6 lbs P/ac/yr. The highest values are measured during years of high precipitation or extreme runoff events. If rainfall is held constant, higher P loss would come from steeper land, land near waterways, erosive soils, erosive management practices, and land with surface manure or fertilizer applications. Furthermore, the size of the watershed matters. Higher per-acre P loads will be measured in runoff from a half-acre plot than in the drainage of a 200 mi^2 watershed where deposition and adsorption of P occur throughout the watershed. For example, rates of 18 lbs P /ac have been measured in runoff from small research plots.

Thus, agricultural loading factors for a watershed should be selected to match:

- Size of the watershed
- Ag management practices
- Soil and landscape characteristics

Even when all three of these features are kept constant, actual P loads will vary substantially from year to year depending on weather patterns.

Use the following steps to improve the estimate of phosphorus loss from ag land

1. **Subdivide agricultural land.**
   As much as possible, divide agricultural acreage into subcategories of cropping systems: row crops with manure applications, row crops with no manure applications, and pasture or perennials. Further subdivisions by cropping system or landscape types may be helpful. Default loading factors for these basic categories are shown in Table 1.

Table 1: PSAT default loading factors.

Row crops with manure applications	0.8
Row crops with no manure applications	0.6
Pasture or perennials	0.2
Mixed agriculture	0.5

See explanation of factors in "Documentation" on page 17.

2. **Use the Minnesota Phosphorus Index (MN P Index) to refine the loading factors.** The MN P Index (available at www.mnpi.umn.edu) analyzes P loss risk from a farm field. It can account for soil type, landscape, tillage practices, cropping systems, and manure application practices. For each ag land use category, create one or more scenarios that represent the typical farming systems in your watershed. Use the MN P Index to determine the P loss risk rating for each scenario. The MN P Index generates a P loss risk estimate for a field, not on a per-acre basis, but it can be used to suggest refinements to loading estimates. Use Table 2 to convert the MN P Index results to a loading factor to be used in column H of the Primary Sources sheet in PSAT.

Table 2: Converting MN P Index results to PSAT loading factors.

	MNPI results	**PSAT loading factor**
Very low	<1	0.1 – 0.2
Low	1 – 1.9	0.2 – 0.5
Medium	2 – 3.9	0.5 – 0.9
High	4 – 5.9	1.0 – 1.4
Very high	>6	>1.4

3. **Choose a range of loading factors.**
   Based on the results from Step 2 and other relevant watershed data (see Appendix A: Ag P Load Data), choose low and high loading factors for each ag land use category. Calculate PSAT results for both. By presenting results for a low and high estimate of agricultural P loss, you can account for two sources of uncertainty: 1) Actual long term average P loads are unknown; use a range to illustrate the possible values. 2) P loads vary widely from year to year; use a range to illustrate possible values in low versus high runoff years.
   How much interannual variation can be expected? Of the watershed data used to support this model, on average, individual sites varied more than six-fold between high and low P loss years. These watersheds were all less than 200 sq. mi. MPCA (2004) used a factor of 3.2 difference between P loss in wet years vs. dry years for estimating P loading from agricultural land for the Upper Mississippi River Basin.

4. **Document your choices.**
   Provide a justification for the loading factors selected.

Cautions

Size of watershed

PSAT is intended for small to medium-sized watersheds. Loading factors for rural areas are based on data from watersheds less than 200 sq miles, so the PSAT should not be applied to larger watersheds. In urban watersheds (more than 30% urban development), the maximum watershed size should be limited to 20 square miles. This is because the urban runoff estimate is based on the Simple Method, which was originally designed for development lots less than 1 mile square

The tool could be applied to larger watersheds (e.g. 8-digit HUCs) if loading factors are adjusted accordingly. Consider applying the loading factors only to land within a 100 meters from surface water as described in the statewide phosphorus assessment (MPCA, 2004. Especially Appendices C and I.). The MPCA study used the coefficients shown in Table 3 for the Upper Mississippi River basin.

Table 3. Export coefficients for phosphorus load calculations for the Upper Mississippi River Basin.

	Kg/ha/y	Lb/a/y
Deciduous Forest	0.075	0.067
Evergreen Forest	0.123	0.109
Mixed Forest	0.13	0.116
Shrubland	0.129	0.115
Grasslands/ Herbaceous	0.169	0.150
Agriculture	0.39	0.35

From MPCA (2004): Table 8 of Appendix I, and Table 3 of Appendix C.

Relative, not actual loads

This tool is not a calibrated model so results represent relative contributions or relative changes. It cannot reproduce actual in-stream loads.

The load reductions on the “Management Practices” worksheets are sometimes calculated as a percent efficiencies. However, some are calculated separately using a different method than used to calculate primary and secondary loading. So use caution when comparing the two values (primary or secondary load versus load reduction from management practices. Use the load reduction estimates to illustrate the relative magnitude of reductions possible.

Annual averages

PSAT results are annual averages that give no indication of variation within or between years. When planning treatment, consider critical conditions during the year and plan for major events such as snowmelt or large runoff events

Uncertainty

Conservative assumptions in the model provide some margin of safety, however and explicit margin of safety should be incorporated where specific targets are to be met, such as in a TMDL study.

High soil test P

PSAT cannot account for high soil test P levels in rural land near water bodies. The MNPI should be used in these situations to estimate risk.

Forest P loads

Forest P loads are assumed to be minimal in the PSAT calculations, but high loads are possible from isolated locations with high compaction or high snowmelt runoff.

Internal loading

PSAT does not consider internal loading as a source of P.

Form of P

PSAT does not differentiate between dissolved and particulate P. The tool only considers total P on the assumption that all P has the potential to become available.

Watershed P loading

PSAT is a model of lake P loading, not watershed P loading. For example, P may buildup in a watershed under septic tanks and in fields with heavy manure applications. But if there is no transport mechanism, the P may not be carried to the lake to increase lake loading.

Documentation

Development of PSAT

The Phosphorus Source Assessment Tool is a modification of the Watershed Treatment Model (WTM) created by the Center for Watershed Protection. (See References, page 21, for download instructions.) Several significant modifications were made:

- The WTM was designed primarily to assess stormwater runoff from urbanized watersheds. Several agricultural land use categories were added to make it more useful in rural watersheds.
- Default loading factors were changed based primarily on data from Minnesota and Wisconsin.
- The PSAT focuses on phosphorus. Components for nitrogen and bacteria were removed from the WTM.
- A new results reporting worksheet was added with pie graphs of the results.

The name was changed to the Phosphorus Source Assessment Tool to reflect these changes, to emphasize that this tool is not a calibrated model, and because we are not emphasizing the treatment component of the model.

Other modifications to the WTM include:

- Adding the option to account for septic systems that are an imminent threat to public health and safety (ITPHS) because counties routinely survey ITPHS systems along with failing and complying systems.
- Adding the option to input subsoil P levels. This value, instead of surface soil P, is used in the channel erosion estimate.
- Deleting the combined sewer overflow component because combined sewers have been all but eliminated from Minnesota.
- In the livestock calculation, deleting poultry because they are virtually never on exposed lots, and adding horses because they occasionally are concentrated near water sources.
- Adding the option to indicate the P content of road sand. WTM did not consider road sand to be a source of P.
- Deleting the lawn subsurface flow component because it has little significance for phosphorus.

Urban land uses

Phosphorus loss from urban land (residential, commercial, roadway, and industrial) is calculated by using the Simple Method to estimate runoff based on percent impervious area and multiplying by a P concentration. The Simple Method is:

Load (lb P per acre) = mg P/L * Rainfall (in) * 0.9 * (0.05+0.009* %imperv) * 0.226

(0.226 is a unit conversion factor)

Default event mean concentrations (Table 4) are based on Bannerman et al. (1992 and 1993), documentation for the WTM (Caraco 2001)

Table 4. PSAT default P concentrations in urban runoff.

Urban land use	Default P concentration in runoff
Roadways	0.5 mg/L
Commercial	0.3 mg/L
Industrial	0.4 mg/L
Residential	0.4 mg/L

Rural land uses

Phosphorus loss from non-urban lands is calculated using default loading factors (column K) in pounds of P per acre. No estimate of runoff is made.

Loading factors are estimates of the annual amount of phosphorus delivered to the lake or other endpoint of a watershed, divided by the total number of acres in the watershed. In reality, phosphorus comes from critical areas in the landscape and does not flow equally from all areas.

Agricultural land uses

P loading from agricultural land was based on the studies described in Table 5, and on analyses done with the MN Phosphorus Index (MN PI). A scenario representing land use in two Nicollet County watersheds (Birr 2006) was analyzed in the MN PI. The resulting risk factor (3.3) was four times the measured P loss of 0.8 lbs P/acre. Thus, we assumed that actual P loss is 0.24 times a MNPI risk factor. We modeled typical ag scenarios with and without manure and used the 0.24 factor to convert MNPI results for each scenario to the loading factors used in PSAT. P loss risk from row crops with manure applications varied widely depending on the amount and method of application.

Table 5. Basis for agricultural loading values.

Value	Description of source
0.8 lb/a	The average of total P loads from 13 studies of cropland in the Midwest larger than 1 hectare from the MANAGE database (Harmel, et al. 2006). All sites were corn and/or soybeans, 4 to 150 acres. Averages ranged from 0.12 to 1.6 lb/ac. Four of the 5 sites that were >1 lb/ac were from MO which has higher precip than MN. P loads decrease as field size increases, so studies on very small plots were eliminated, including those in Morris MN in the late 1960's (Young et al. 1977; Burwell at al. 1975) where rates of 5 to 33 kg/ha were measured.
0.8 lb/a	Average of two 2800-acre watersheds in Nicollet County MN measured for three years (Birr 2006). Annual measurements ranged from 0.55 to 1.2 lb/ac. No association observed between P load and increased BMPs in one of the watersheds. (BMPs included switching from fall moldboard (MB) to chisel (FC) plowing, replacing open inlets, and nutrient management planning.) Management was generally corn/soybean rotation, 20% of acres got manure, 25% of acres had fall MB, 66% had FC.
1 lb/a	Average P load from 20 Wisconsin watersheds with >80% agricultural land, ranging from 2 to 200 sq. mi. (Corsi et al. 1997). P loads from agricultural watersheds tended to be higher than loads from either urbanized watersheds or predominantly forested/water watersheds. Values over 1 lb/a generally came from sites in the steeper driftless area of southwest WI.
0.4 lb/a	Agricultural loading factor used for the Upper Mississippi River Basin in the MPCA study of statewide phosphorus sources (Barr 2004).
0.89 lb/a	Loading factor used in WiLMS (Panuska and Kreider 2003) as the "most likely" value for row crop agriculture. "Low" and "high" values used in WiLMS were 0.45 and 2.67, respectively. Their values are based on data from smaller watersheds, i.e. ~20 sq. mi. WiLMS is a model used in Wisconsin for similar purposes as PSAT.
0.2 lb/a	The average of total P loads from five studies of pasture runoff in the Midwest from the MANAGE database (Harmel, et al. 2006). One site was 43 ha, the remainder were 6.3 ha or less. So these results are probably high for the scale of a lake watershed. Three were rotationally grazed (0.1-0.28 lb/ac). Two studies in the database were excluded because the pastures were used as winter feeding lots. Total P losses from these sites were 0.9 and 1.7 lb/ac. Another study was excluded because it was alfalfa in rotation with corn and oats (0.7 lb/ac).
0.27 lb/a	The loading factor used in WiLMS (Panuska and Kreider 2003) as the "most likely" value for pastures. "Low" and "high" values were 0.09 and 0.45, respectively.

Rural development

The P loading factor of 0.2 lb/a/yr is the result of the Simple Method (explained on page 18**Error! Bookmark not defined.**) assuming 5% impervious cover, 26 inches of precipitation, and 0.4 mg P /L. This value makes sense because it is higher than forest losses but lower than low density residential losses.

WiLMS (Panuska and Kreider 2003) used a loading factor of 0.09 lb/a as the "most likely" value for rural residential acres (define as larger than one-acre lots). "Low" and "high" values are 0.04 and 0.22, respectively.

Forest, brush, and grassland

PSAT uses a single loading factor of 0.1 lb/a for all areas of natural vegetation. The MPCA phosphorus study (Barr 2004) used loading factors of 0.07 to 0.15 lb/a for natural plant communities, but only considered acreage within 100 m of water. WiLMS (Panuska and Kreider 2003) used a loading factor of 0.08 lb/a as the "most likely" value for forest land, and 0.04 and 0.16 as the "low" and "high" values.

Open water / Atmospheric deposition

The P loading factor of 0.2 lb/a for open water at the bottom of the watershed represents inputs from atmospheric deposition. The BATHTUB model uses a default value for atmospheric deposition of 0.27 lb/a. The MPCA phosphorus study (Barr 2004) uses a value of 0.15 lb/a for the Upper Mississippi River Basin. WiLMS (Panuska and Kreider 2003) used values of 0.1 lb/a and 0.3 lb/a for wetlands and lakes, respectively. WiLMS does not differentiate by location in the watershed.

Septic systems

Phosphorus concentrations in septic tank effluent of 1, 3, and 5 mg/L for conforming, failing and ITPHS systems, respectively, were suggested by University of Minnesota septic system specialists (Sara Christopherson, personal communication). The value of 1 mg/L for conforming systems is reasonable for coarse soils but is probably high for finer soils.

Default rates of 25% of septic systems failing and 5% systems ITPHS (Imminent Threat to Public Health and Safety) are averages for central Minnesota counties from 2005 annual reports.

The default value of 70 gallons of waste per person day was retained from the Watershed Treatment Model. It is slightly higher than the estimate of 60.4 gallons from Mayer et al. (1999).

People generate about 2 lbs of P per person per year. This ends up in the septic tank, in the soil, in the water, or exported from the area.

Livestock

The manure P delivery factor was set at 3% on David Schmidt’s suggestion and to better match results from the MinnFARM model (David Schmidt, UMN manure feedlot specialist, personal communication).

Geese

PSAT assumes an annual P production of 0.8 lbs per goose, which is the average of the two data sources: Scherer et al. (1995) and Manny et al. (1994). Scherer et al. used the following estimates: P is 1.87% of goose droppings (dry weight), geese average 8 lbs live weight, and annual P production per bird is 1.23 lbs or 0.15 lbs P per lb of live weight. Manny et al. estimated an average live bird weight of 5.6 lbs (measured during molting in 1955) and 0.07 lbs of P per lb of live weight.

Scherer et al. found little link between the amount of waterfowl and water quality. They pointed out that nutrients cycle through the birds quickly, so much of the P comes from food that was eaten in or very near the lake, i.e., goose droppings may be more internal than external loading.

Cormorants and pelicans were not considered because no information about their effects was readily available.

Marine toilets/recreation

The estimate of direct human waste includes two separate calculations. The first follows the assumptions of the Watershed Treatment Model (WTM) for estimating dumping from marine toilets. The WTM assumes 8 gallons of waste per person per day with 10 mg/L phosphorus.

The second calculation is based on monitoring done on Granite Lake in January and February of 2007 (Wright County, Lake ID#086-0217; Raymond Rau, personal communication). They observed an average of 3.8 urine spots near each ice fishing site (ice house or cluster of holes) per week. According to Etnier et al. (2005), human waste contains 365 g P (67%) in urine and 183 g P (33%) in feces per year. Thus, assuming four urinations per day (no reference), each urine spot would contribute 0.25 g P.

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Watershed Treatment Model. Developed by the Center for Watershed Protection.
To download the WTM, go to http://www.stormwatercenter.net/. Click on Monitor/Assess, then click on Watershed Treatment Model near the top of the page.
For WTM documentation, go to the Center for Watershed Protection's list of Technical Manuals at http://www.cwp.org/PublicationStore/TechResearch.htm.

Acronyms

CWP	Center for Watershed Protection (www.cwp.org)
du	dwelling units
gpcd	gallons per capita per day
gpd	gallons per day
HDR	high density residential
HUC	Hydrological Unit Code (http://www.dnr.state.mn.us/watersheds/index.html)
ITPHS	Imminent Threat to Public Health and Safety (Refers to a septic tank that drains effluent directly into surface water or to the ground surface.)
LDR	low density residential

LMIC	Land Management Information Center
MDR	medium density residential
mg/L	milligrams per liter (equivalent to ppm)
MinnFarm	Minnesota Feedlot Annualized Runoff Model (http://www.manure.umn.edu/applied/open_lots.html)
MNPI	Minnesota Phosphorus Index (www.mnpi.umn.edu)
MPCA	Minnesota Pollution Control Agency
MPSAT	See PSAT.
NPDES	National Pollutant Discharge Elimination System (An EPA program that regulates discharges of pollutants from point sources such as waste water treatment plants or industrial waste.)
P	phosphorus
ppm	parts per million. In the case of nutrient concentrations in water, ppm is equivalent to mg/L.
PSAT	Phosphorus Source Assessment Tool, also called the Minnesota PSAT (MPSAT)
sf	square feet
SSO	Sanitary Sewer Overflow (leaking into and out of sanitary sewer systems)
TMDL	Total Maximum Daily Load (the level of a pollutant input that will maintain the desired level of water quality in a water body)
TP	Total phosphorus
TSS	Total suspended solids
WDNR	Wisconsin Department of Natural Resources
WiLMS	Wisconsin Lake Modeling Suite (Panuska and Kreider, 2003)
WTM	Watershed Treatment Model (http://www.stormwatercenter.net/)

University of Minnesota
EXTENSION

Best Management Practices for Nitrogen Use:
IRRIGATED POTATOES

BEST MANAGEMENT PRACTICES FOR NITROGEN APPLICATION

Best Management Practices for Nitrogen Use: Irrigated Potatoes

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Summary

Nitrogen (N) is an essential plant nutrient that contributes greatly to the economic viability of irrigated potato production. Unfortunately, the nitrate form of N can leach into groundwater if N is not managed properly. Contamination of water resources by agricultural production systems will not be tolerated by the public and could lead to laws regulating the use of N fertilizers if this contamination is not minimized.

Research-based Best Management Practices (BMPs) have been developed specifically for irrigated potatoes and integrated into the BMPs that were developed previously for other agronomic crops on coarse-textured soils. Various strategies are provided that take into account N rate, timing of application, method of application, and N source. Optimum N management also depends on the variety grown and its harvest date, so basic principles are similar but specific recommendations differ for early, mid-season, and late-season varieties.

The main objectives of these BMPs are to maintain profitability and minimize nitrate leaching. By following these recommendations, the threat of fertilizer regulations can be avoided and a more profitable and better community can be attained.

Introduction

Nitrogen is an essential plant nutrient that is applied to Minnesota crops in greater quantity than any other fertilizer. In addition, vast quantities of N are contained in the ecosystem, including soil organic matter. Biological processes that convert N to its mobile form, nitrate (NO_3), occur continuously in the soil system. (For greater understanding see: ***Understanding Nitrogen in Soils*** **AG-FO-3770**). Unfortunately, nitrate can move (leach) below the rooting zone and into groundwater.

In response to the Comprehensive Groundwater Protection Act of 1989, a Nitrogen Fertilizer Management Plan was developed with the purpose of managing N inputs for crop production to prevent degradation of Minnesota water resources while maintaining farm profitability. The central tool for achievement of this goal is the adoption of Best Management Practices for Nitrogen. Best management practices for N are broadly defined as economically sound, voluntary practices that are capable of minimizing nutrient contamination of surface and groundwater. The primary focus of the BMPs is commercial N fertilizers; however, consideration of other N sources and their associated agronomic practices is necessary for effective total N management.

General BMPs for all Regions of the State

The use of BMPs is based on the concept that accurate determination of crop N needs is essential for profitable and environmentally sound N management decisions. General BMPs that apply to all cropping regions in the state are listed below:

- Adjust the N rate according to a realistic yield goal (for all crops except corn and sugar beets) and the previous crop
- Do not apply N above recommended rates
- Plan N application timing to achieve high efficiency of N use
- Develop and use a comprehensive record-keeping system for field specific information.
- If manure is used, adjust the N rate accordingly and follow proper manure management procedures to optimize the N credit:
    - Test manure for nutrient content
    - Calibrate manure application equipment
    - Apply manure uniformly throughout a field
    - Injection of manure is preferable, especially on steep sloping soils
    - Avoid manure application to sloping, frozen soils
    - Incorporate broadcast applications whenever possible

For more detailed information on making the most efficient use of manure nutrients and avoiding potential adverse effects on water quality, see the University of Minnesota Extension publications listed at the end of this bulletin.

The Need for Best Management Practices for Irrigated Potatoes

Most of the BMPs developed for crop production in Minnesota have been based on research with corn and small grains. Management strategies for coarse-textured soils can be found in: ***Best Management Practices for Nitrogen Use on Coarse Textured Soils*** (**08556, revised 2008**). In contrast to most agronomic crops, potatoes are a relatively shallow rooted crop and require intensive management to promote growth and yield. In addition, adequate N needs to be available to maintain both yield and tuber quality. The shallow root system of potatoes, the need for adequate N, and the extensive production on sandy soils greatly increase the potential of nitrate contamination of shallow aquifers under irrigated potato production. Fortunately, University of Minnesota research strongly suggests that environmental impacts can be minimized by using nitrogen BMPs specifically designed for potatoes.

While the general BMPs developed for corn and small grains listed above will also apply to irrigated potato production, BMPs focused on irrigated potato production are described within this bulletin so that more precise management practices can be followed. The research-based nitrogen BMPs discussed here, therefore, have been tailored specifically for potato production on irrigated, coarse-textured soils. These BMPs are not only environmentally sound, they are also potentially more profitable. When N leaches below the potato root zone, where it can degrade water quality, it also becomes a purchased input that is lost from the crop production system. Efficient N management that minimizes losses provides both economic and environmental benefits.

Specific Nitrogen Best Management Practices for Irrigated Potatoes

Nitrogen management considerations for irrigated potatoes include decisions regarding: 1) N rate, 2) timing of N application, 3) use of diagnostic procedures to determine N needs during the growing season, 4) effective water management, 5) sources of N, and 6) establishment of a cover crop after harvest. Suggested N management approaches for different varieties and harvest dates of irrigated potatoes are presented following the discussion on BMPs.

Selecting a Realistic Nitrogen Rate

The rate of N to apply to irrigated potatoes primarily depends on the cultivar and date of harvest, expected yield goal, amount of soil organic matter, and the previous crop. Rates of N recommended for potatoes can be found in ***Nutrient Management for Commercial Fruit and Vegetable Crops in Minnesota*** (**AG-BU-5886-F**) and in Appendix A of this document. Response to N by potato is typical of other crops in that the first increment of fertilizer usually brings about the greatest response in yield, followed by a more gradual increase with succeeding increments of N (Table 1). As the N rate increases, however, the potential for losses also increases. In addition to environmental concerns due to excessive N applications, high rates of N can detrimentally affect potato production by promoting excessive vine growth, delaying tuber maturity, reducing yields, decreasing specific gravity, increasing brown center, and inducing knobby, malformed, and hollow tubers. Selecting a realistic N rate is therefore important from both a production and an environmental standpoint. Unfortunately, the effect of excess N on tuber quality is dependent on soil moisture and temperature as well as the cultivar grown. This means that the N rate at which detrimental effects will occur is difficult to predict.

Base N rate on variety, harvest date, and realistic yield goals

Different potato varieties and differences in harvest date will have a pronounced effect on yields and yield goals. Because of lower yield and earlier harvest, early maturing varieties like Red Norland (Table 2) generally require less N than later maturing varieties, such as Russet Burbank (Table 1). A definition of harvest date is as follows: Early - vines are killed or the crop is green dug before August 1; Mid-season - vines are killed or the crop is green dug before September 1; Late –vines are killed or the crop is green dug September 1 or later. Unlike corn and sugar beets, the yield goal concept is still being used to guide N recommendations for potatoes, in conjunction with variety and harvest date, until a more complete measure of the N supplying capacity of the soil is available. Currently N recommendations are also adjusted for the amount of soil organic matter, with higher rates for low organic matter soils than for medium to high organic matter soils which have a greater capacity to release plant-available N. Yield goal for potatoes is based on the total yield obtained rather than the marketable yield, but the two are generally well-correlated. An overestimation of the yield goal will result in excessive applications of N, which can potentially result in nitrate losses to groundwater.

Table 1. Response of Russet Burbank potatoes to nitrogen rate at Becker MN, 2004-2005.

N rate	Marketable*	Total
lb N/A	------------ cwt/A	------------
0	299	377
30	326	485
80	423	550
120	547	651
160	531	629
180	583	667
240	611	690
320	594	663

*Marketable tubers are greater than 3 oz in size with no visible defects.

Table 2. Response of early harvested Red Norland potatoes to nitrogen rate at Becker MN, 1995-1997.

N rate	Total and Marketable
lb N/A	-- cwt/A --
125	336
165	325
205	324
245	317
285	303

Account for nitrogen from previous crops

Previous crop can also affect N needs. Legumes in a crop rotation can supply significant N to subsequent crops. Research in Wisconsin on sandy soils (Kelling, et al., 1991) found that maximum potato yields following sorghum sudangrass required 40 lb/A more N than following red clover and 80 lb/A more N than when following alfalfa. Similar results from a 20 year study in the Netherlands found that N requirements for optimum potato yield following oats were 60 lb N/A greater than following red clover and 90 lb N/A greater than following alfalfa (Neeteson, 1989). Failing to account for N supplied by legumes can lead to a buildup of soil N and increase the potential for nitrate leaching.

Test irrigation water for nitrogen content and adjust N fertilizer accordingly

The amount of N in the irrigation water should also be considered when adjusting N rates. Nitrate in irrigation water can supply a portion of the N required for crop production. In N calibration studies on potatoes at Becker MN, the nitrate-N concentration in irrigation water ranged from 7 to 10 ppm (parts per million). This concentration of N in the water should be considered as background, but amounts above 10 ppm should be credited as fertilizer N. Additionally, the time to credit N from irrigation water is when the plant is actively growing and taking up N. For late season potatoes this occurs from 20 to 60 days after emergence (Figure 1). Because nitrate-N levels in irrigation water can vary, samples of irrigation water need to be tested annually during the pumping season to determine approximate nitrate-N concentrations.

If nitrate-N in irrigation water is one ppm, then each inch of irrigation water applied is equal to 0.225 pounds of N applied per acre. As an example, if irrigation water is found to have 20 ppm nitrate-N and 9 inches of water are applied during the active part of the growing season, then about 40 lbs of N/A would be supplied with the water (0.225 * 9 * 20). After subtracting the background amount of 20 lb N/A, the remaining 20 lb N/A should be credited toward the total amount of N applied. In practice, you will not know how much N was applied in irrigation water until after the active growth period when all or most of the N fertilizer has already been applied, so for the current growing season you will have to estimate the N credit for irrigation water from records of previous years.

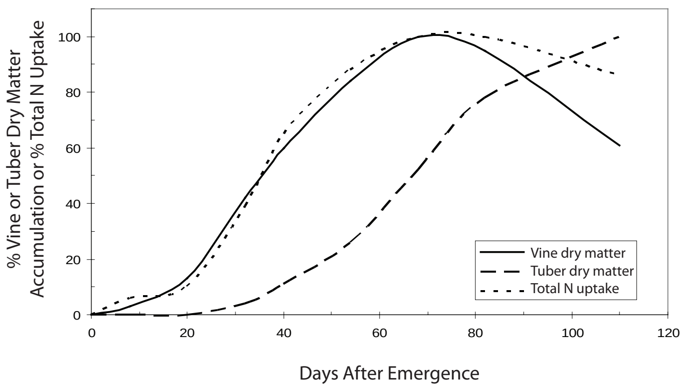

Figure 1. Relative tuber growth, vine growth and total nitrogen uptake by the potato crop. Based on data from the Russet Burbank variety.

Timing of Nitrogen Application: Match N Application with Demand by the Crop

One of the most effective methods of reducing nitrate leaching losses is to match N applications with N demand by the crop.

Do not fall apply N on sandy soils (sands, loamy sands, and sandy loams)

Do not use more than 40 lbs N/A in the starter for mid/late season varieties

Do not use more than 60 lbs N/A in the starter for early harvested varieties

Nitrogen applied through the hilling stage should be cultivated/incorporated into the hill

Plan the majority of soluble N inputs from 10 to 50 days after emergence

Nitrogen applications in the fall are very susceptible to leaching. Nitrogen applied early in the season when plants are not yet established is also susceptible to losses with late spring and early summer rains. Most nitrification inhibitors are not registered for potatoes and therefore cannot be recommended. Peak N demand and uptake for late season potatoes occurs between 20 and 60 days after emergence (Figure 1). Optimum potato production depends on having an adequate supply of N during this period. The recommendation is to apply some N at planting for early plant growth and to apply the majority of the N in split applications beginning slightly before (by 10 days) the optimum uptake period. This assures that adequate N is available at the time the plants need it and avoids excess N early in the season when plant growth is slow and N demand is low.

Research at the Sand Plain Research Farm at Becker, with full season varieties like Russet Burbank, demonstrates that nitrate movement below the root zone can be reduced by lowering the amount of N in the starter fertilizer without affecting yields (Table 4). Starter fertilizer should contain no more than 40 lb N/A for full season varieties. Uptake of N by the crop (vines plus tubers) increases when split N applications are used compared with large applications applied before emergence. Nitrogen applied through the hilling stage should be incorporated into the hill to maximize availability of the N to the potato root system.

Just as N fertilizer applied too early in the season can potentially lead to nitrate losses, so can N fertilizer applied too late in the season. Nitrogen applied beyond 10 weeks after emergence is rarely beneficial and can lead to nitrate accumulation in the soil at the end of the season. This residual nitrate is then subject to leaching.

For determinate early harvested varieties like Red Norland, higher rates of N in the starter may be beneficial (Table 5). These varieties tend to respond to higher rates of early N than indeterminate varieties, but the total amount of N required is generally lower because of lower yield potential and early harvest. In addition, late application of N to these varieties will tend to delay maturity and reduce yields, particularly if the goal is to sell for an early market. In many cases it is not possible to know when the exact harvest date will be as this will depend on market demands as well as weather conditions during the season. Because of these unknowns it is important to have some flexibility in both rate and timing of N application.

Table 4. Nitrogen starter effects on Russet Burbank potato yield and nitrate-N leaching to the 4½ ft depth. Means of 1991 and 1992.

Timing of N application			Yield		NO_3-N
Planting	Emergence	Hilling	Total	Marketable	Leaching
lb N/A			cwt/A		lb/A
0	0	0	359.9	292.3	18
0	120	120	602.7	532.8	76
40	100	100	594.0	518.5	114
80	80	80	612.9	519.7	134
120	60	60	589.4	493.5	158

Errebhi et al., 1998.

Table 5. Nitrogen starter effects on Red Norland potato yield, Becker - 1995-1997.

Timing of N application			Total Yield
Planting	Emergence	Hilling	
lb N/A			cwt/A
25	70	70	325
45	60	60	328
65	50	50	338
85	40	40	337

Use petiole analysis to aid in making post-hilling nitrogen applications

Increases in N use efficiency have been shown when some of the N is injected into the irrigation water after hilling (fertigation). Because the root system of the potato is largely confined to the row area during early growth, do not fertigate until plants are well established and potato roots have begun to explore the furrow area between rows. This is usually about three weeks after emergence. Nitrogen applications after this time are most beneficial in years when excessive rainfall occurs early in the growing season (Tables 6 and 7). In dry years with minimal leaching, N applications later than 16 days after emergence show little if any advantages from a production standpoint over applying all of the N by that stage (Tables 7 and 8). However, leaching losses can still be reduced.

Table 6. Effect of N applications later than 16 days after emergence on Russet Burbank yield, Becker – 1991 (high leaching year).

Timing of N application[1]				Tuber Distribution					
Plant.	Emerge.	Post Emerge.	Late PE	Culls	<3 oz	3-7oz	7-14oz	>14oz	Total
--------- lb N/A ---------				------------- cwt/A -------------					
40	40	40	0	23	51	240	158	5	477
80	80	80	0	28	47	224	179	8	486
40	40	40	80	36	42	221	200	13	512

[1]Planting, emergence, 16 days post-emergence, and two late post-emergence applications more than 16 days after emergence of 40 lb N/A per application.

Table 7. Effects of excessive irrigation and nitrogen rate, source, and timing on cumulative NO_3-N leaching to the 4 ft depth (Zvomuya et al., 2003).

N Rate	N Source	Irrigation	
		Standard	Excessive
		NO_3-N leaching	
--- lb N/A ---		----------- lb N/A -------------	
0	----	46	61
125	urea[1]	59	88
125	PCU[2]	55	84
250	urea[3]	75	204
250	PCU[2]	50	128
250	posthill[4]	80	121

[1]25 lb N/A at planting, 50 lb N/A at emergence, and 50 lb N/A at hilling.
[2]Polyolefin-coated urea in a single application at planting.
[3]25 lb N/A at planting, 112 lb N/A at emergence, and 112 lb N/A at hilling.
[4]25 lb N/A as urea at planting, 72 lb N/A as urea at emergence, 72 lb N/A as urea at hilling, and 40 lb N/A as equal amounts of N from urea and ammonium nitrate at 3 and 5 weeks after hilling.

Table 8. Effect of N applications later than 16 days after emergence on Russet Burbank yield, Becker – 1992 (low leaching year).

Timing of N application[1]				Tuber Distribution					
Plant.	Emerge.	Post Emerge.	Late PE	Culls	<3 oz	3-7oz	7-14oz	>14oz	Total
--------- lb N/A ---------				------------- cwt/A ------------					
40	40	40	0	32	58	267	158	3	518
80	80	80	0	31	53	281	223	12	601
40	40	40	80	29	58	246	195	14	541

[1]Planting, emergence, 16 days post-emergence, and two late post-emergence applications more than 16 days after emergence of 40 lb N/A per application.

If applications of N later than 16 days after emergence are used, then 2/3 to 3/4 of the recommended N fertilizer should be applied by that stage. Timing of the remainder of the N applications should be based on petiole nitrate-N levels determined on either a dry weight or sap basis. Table 9 shows suggested sufficiency ranges for Russet Burbank potatoes through the growing season. Other potato varieties may vary slightly in their sufficiency ranges. However, the ranges in Table 9 are still a suitable starting point to adjust post-emergence N applications for other varieties. Typically if N is needed, 20 to 40 lb N/A can be injected per application.

Another potential in-season monitoring tool is soil testing for plant-available inorganic N in the upper 12 to 18 inches of the soil. Samples should be collected from the hill area in sets of five soil cores and analyzed for nitrate-N and ammonium-N. One core should be from the top of the hill, one core from each side of the hill half-way up the side slope, and one core from each side at the base of the hill. Initial research on in-season soil testing suggests that sufficiency levels for total inorganic N (nitrate-N + ammonium N) in the 0-1 ft depth for Russet Burbank are about 140 lb N/A (35 ppm) during initial bulking (June) and 80 lb N/A (20 ppm) during early bulking (July). Additional research is necessary to calibrate in-season soil tests and determine how much N to apply at specific soil test levels. Soil testing should be viewed as a tool to help fine tune N management and used in conjunction with, not as a substitute for, petiole testing.

One danger of relying on N applications through the irrigation system occurs when rainfall patterns during the time for fertigation are adequate or excessive. Applying N through the system in this case may potentially lead to an increase in nitrate leaching if high amounts of irrigation water are also applied. In situations where there is a demand for N, but rainfall has been adequate or excessive, low amounts (less than 0.3 inch) of water should be applied with the N fertilizer. Another potential problem with delayed N application occurs when the potato crop dies back early due to insects or diseases. In this situation, N applied more than 16 days after emergence may not be used as efficiently and they may increase N leaching losses. It is essential therefore, that an integrated cropping approach be taken to minimize nitrate leaching losses.

Selecting Appropriate Nitrogen Sources

Do not use fertilizers containing nitrate in the starter

Each fertilizer N source used for potatoes has advantages and disadvantages, depending on how they are managed. However, because leaching often does occur in the spring, fertilizer sources containing nitrate (i.e. UAN-28 and ammonium nitrate) should be avoided at planting. Ammonium sulfate, diammonium phosphate, monoammonium phosphate, poly ammonium phosphate (10-34-0), or urea are the preferred N sources for starter fertilizer. Advantages of urea compared with ammonium nitrate are greater availability, lower cost, and delayed potential for leaching. Disadvantages of urea are that it is hygroscopic (attracts water), it must be incorporated after application or ammonia volatilization losses may occur, and its slow conversion to nitrate in cool seasons may reduce yields. Anhydrous ammonia may be beneficial in delaying the potential for leaching losses; however, positional availability of the N in relation to the hill may be a problem with sidedress applications. Further research needs to be conducted on the use of anhydrous ammonia for potato.

Table 9. Petiole nitrate-N sufficiency levels for Russet Burbank potatoes on a dry weight and sap basis.

Time of Season/ Stage of Growth	Sap NO_3-N	Dry wt. NO_3-N
	------------- ppm -------------	
Early Vegetative/tuberization (June 15 - June 30)	1200 – 1600	17,000 - 22,000
Mid Tuber growth/bulking (July 1 - July 15)	800 – 1100	11,000 - 15,000
Late Tuber bulking/maturation (July 15 - August 15)	400 – 700	6,000 - 9,000

Table 10. Effect of a controlled release N source on potato (Russet Burbank) yield, Becker – 2005.

N rate[1]	N source			
	Urea	ESN[2]	Urea	ESN[2]
	Total Yield		Marketable Yield	
---- lb N/A ----	---------------- cwt/A ----------------			
80	643	679	499	526
160	698	695	579	582
240	676	677	583	560
320	660	625	576	519
240 (ESN emergence)	-	737	-	631

1All treatments received 40 lb N/A from diammonium phosphate at planting.
2ESN was applied at planting, except for the second 240 lb N/A rate which was applied at emergence.

Substantial reductions in nitrate leaching can occur if controlled release sources of N are used (Table 7). Controlled release N sources include polymer coated urea that can be formulated to release N over various time intervals. These controlled release sources can also be applied earlier in the season without the fear of nitrate leaching losses. The main disadvantages of controlled release N fertilizer are delayed release to ammonium and nitrate when soil temperatures are cool and the higher cost of many of the products compared to conventional quick release N fertilizers. However, there are some newer slow release fertilizers on the market that are more economical and the cost savings of being able to make a single N fertilizer application rather than multiple applications is another factor to consider. Table 10 shows the yield response to ESN, a relatively low cost controlled release N fertilizer, compared to quick release urea applied using standard split application practices. When ESN was applied at planting there was a reduction in marketable yield at the higher N rates compared with urea, but ESN (240 lb N/A) applied at emergence produced the highest total and marketable yields in the study. Further research with low cost controlled release sources needs to be conducted to evaluate effects on tuber quality and nitrate leaching.

For mid to late season varieties, apply ESN no later than emergence.

ESN for early harvested potatoes (vines killed or green dug before August 1) is not recommended due to slow release of N.

Water Management Strategies

Follow proven water management strategies to provide effective irrigation and minimize leaching

Water management has a profound effect on N movement. While leaching of nitrate due to heavy rainfall cannot be completely prevented, following the N management strategies discussed above will minimize these losses. However over-irrigation, even with optimum N rate applied and proper timing of N application, can cause substantial leaching losses. Therefore, effective water scheduling techniques based on soil moisture content and demand by the crop should be followed to prevent such losses. For more information on irrigation scheduling, refer to: ***Irrigation Water Management Considerations for Sandy Soils in Minnesota***, **AG-FO-3875**.

Cover Crops Following Potatoes

Establish a cover crop following potatoes whenever possible

For early harvested potatoes (July/August), any nitrate remaining in the soil is subject to leaching with rainfall. Establishing a cover crop such as winter rye will take up residual N to minimize this potential loss. An additional benefit of the cover crop is to reduce wind erosion. After the cover crop is killed or plowed under, N will be released from the vegetation the following spring. Cover crops can also be planted after potatoes harvested in September/October, although the purpose here is more for erosion control than to reduce N losses.

Specific Best Management Practices for Irrigated Potatoes on Coarse-Textured Soils

Best management strategies for irrigated potatoes need to be somewhat flexible because of differences due to soil type, unpredictable weather, and the numerous potato cultivars grown. However, some general guidelines should be followed with the understanding that modifications may be necessary to fit specific situations and that fine-tuning BMPs for N is an ongoing process. Based on the research conducted with potatoes on sandy soils, the following best management options for N are suggested (these suggestions are based on research with Russet Burbank, an indeterminate late season variety and Red Norland, a determinate early season variety; response may vary with other varieties):

Mid/late season varieties - Vines killed or green dug August 1 or later

Option 1 - when fertigation is available:

- Apply up to 40 lb N/A in the starter (this amount should be included in meeting the total recommended N rate)
- Apply one-third to one-half of the recommended N at or around emergence and cultivate/incorporate the fertilizer into the hill; if ESN is used, apply no later than emergence and incorporate in the hill
- If hilling at emergence is the final hilling operation, begin fertigation 14-21 days later and apply the remainder of the recommended N in increments not exceeding 40 lb N/A
- If a final hilling operation is done 10-14 days after emergence, apply one-third of the recommended N at that time and cultivate/incorporate the fertilizer into the hill. On

heavier textured soils during rainy periods, it may not be possible to time this application properly due to row closure; in this situation, the N can be applied using fertigation
- Base timing of subsequent N applications on petiole analysis; apply up to 40 lb N/A per application through the irrigation system
- Establish a cover crop after harvest whenever possible

Option 2 - for mid/late season varieties when fertigation is not available:
- Apply up to 40 lb N/A in the starter (this amount should be included in meeting the total recommended N rate)
- Apply one-third to one-half of the recommended N at or around emergence and cultivate/incorporate the fertilizer into the hill; if ESN is used, apply no later than emergence and incorporate in the hill
- Apply the remainder of the recommended N rate at final hilling and cultivate/incorporate the fertilizer into the hill
- Establish a cover crop after harvest whenever possible

Option 1 has generally shown better N use efficiency, particularly during years when excessive rainfall has occurred before hilling. Remember that best management practices are based on the most current research available. As more information becomes available through research efforts, some modification of BMPs may be necessary.

Early season varieties, with or without fertigation - Vines killed or green dug before August 1
- Apply up to 60 lb N/A in the starter (this amount should be included in meeting the total recommended N rate)
- Apply one-third to two-thirds of the recommended N at or around emergence and cultivate/incorporate the fertilizer into the hill
- Apply the remainder of the recommended N rate at final hilling and cultivate/incorporate the fertilizer into the hill
- If fertigation is available, base timing of subsequent N application on petiole analysis; if needed, apply up to 30 lb N/A per application through the irrigation system; avoid late applications of N, because that will delay maturity
- Establish a cover crop after harvest

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Fertilizing Cropland with Poultry Manure, FO-5881

Fertilizing Cropland with Beef Manure, FO-5582

Self-assessment Worksheets for Manure Management Plans

Appendix A

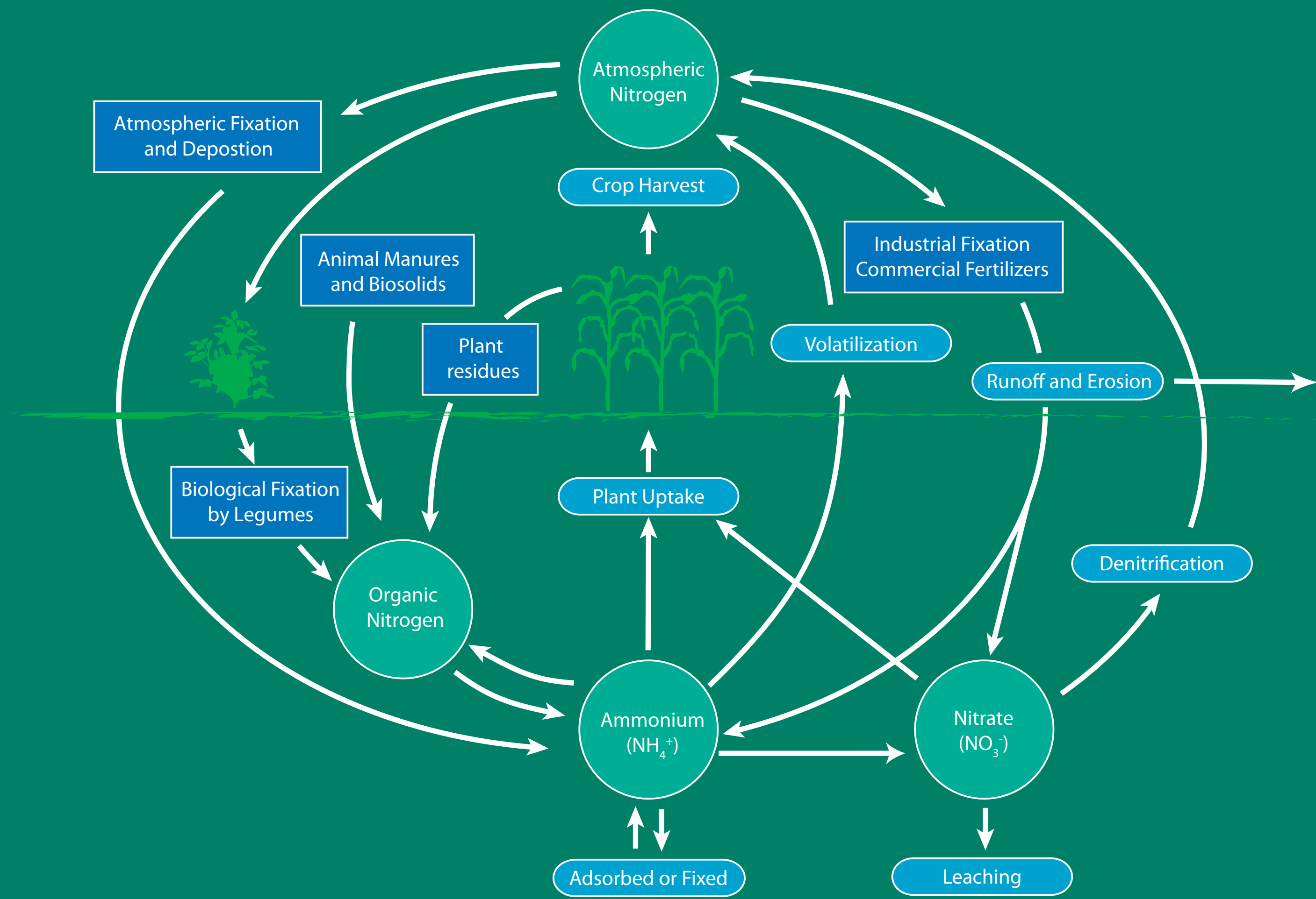
Nitrogen recommendations for irrigated potato production.

		Previous Crop and Organic Matter (O.M.) Level							
		alfalfa (good stand)[1] -O.M.[2]-		soybeans field peas -O.M.-		any crop in group 1 -O.M.-		any crop in group 2 -O.M.-	
Yield Goal[3]	Harvest Date[4]	low	medium to high	low	medium to high	low	medium to high	low	medium to high
cwt/A		N to apply (lb/A)							
<250	Early	0	0	80	60	60	40	100	80
250-299		25	0	105	85	85	65	125	105
300-349		50	30	130	110	110	90	150	130
350–399	Mid	75	55	155	135	135	115	175	155
400–449		100	80	180	160	160	140	200	180
450–499	Late	125	105	205	185	185	165	225	205
500+		150	130	230	210	210	190	250	230

Crops in Group 1	Crops in Group 2		
alfalfa (poor stand)[1]	barley	grass hay	sorghum-sudan
alsike clover	buckwheat	grass pasture	sugarbeets
birdsfoot trefoil	canola	millet	sunflowers
grass-legume hay	corn	mustard	sweet corn
grass-legume pasture	edible beans	oats	triticale
red clover	flax	potatoes	wheat
fallow		rye	vegetables

[1]Poor stand is less than 4 crowns per sq. ft.

[2]Low = less than 3.1% O.M., medium to high = 3.1-19% O.M.; greater than 19% O.M. would be an organic soil and not a coarse-textured soil.



UNIVERSITY OF MINNESOTA
EXTENSION

Best Management Practices for Nitrogen Use: Irrigated Potatoes

PUBLICATION # 08559

Appendix: Ag P Load Data

Watershed-scale phosphorus loss data

Region	Watershed description	Watershed area	lbs P / ac-yr			Source	Site ID
		ac	average	min	max		
Southeast WI	Older loamy and sandy soils; steep, thin drift. 95% agricultural	6400	0.08	0.06	0.09	Corsi et al., 1997	25
WI, eastern forest	Red calcareous clay; lacustrine, till. 87% ag, 10% forest and wetland.	69759	0.13			Corsi et al., 1997	32
Southeast WI	Dairy and specialty crops. Irregular moraines. 96% ag.	47103	0.24	0.13	0.82	Corsi et al., 1997	37
Southeast WI	Older loamy and sandy soils; steep, thin drift. 86% ag, 13% urbanized.	10752	0.30	0.22	0.68	Corsi et al., 1997	27
WI, eastern forest	Red calcareous clay; lacustrine, till. 86% ag, 8% forest and wetland, 6% urbanized.	6080	0.38	0.13	0.92	Corsi et al., 1997	30
Southeast WI	Dairy and specialty crops. Irregular moraines. 85% ag, 8% urbanized, 6% wetland.	23168	0.44	0.28	1.04	Corsi et al., 1997	34
Southeast WI	Dairy and specialty crops. Irregular moraines. 85% ag, 10% urban.	5120	0.51	0.31	0.71	Corsi et al., 1997	28
Southeast WI	Dairy and specialty crops. Irregular moraines. 85% ag, 15% urban.	3648	0.53			Corsi et al., 1997	33
WI, driftless	Steep slopes. A lot of forage and pasture. 82% ag, 17% forest.	6720	0.54	0.10	1.59	Corsi et al., 1997	9
Southeast WI	Dairy and specialty crops. Irregular moraines. 93% ag, 7% forest.	1984	0.72	0.13	2.19	Corsi et al., 1997	36
Southeast WI	Dairy and specialty crops. Irregular moraines. 90% ag, 8% urban.	11712	1.02	0.29	2.25	Corsi et al., 1997	31
WI, Driftless area	Steep slopes. A lot of forage and pasture. 99% ag.	18240	1.07			Corsi et al., 1997	23
WI, eastern forest	Red calcareous clay; lacustrine, till. 99% ag.	9472	1.07	0.97	2.81	Corsi et al., 1997	24
Southeast WI	Older loamy and sandy soils; steep, thin drift. 89% ag, 6% forest and wetland.	127358	1.13			Corsi et al., 1997	35
WI, Driftless area	Steep slopes. A lot of forage and pasture. 99% ag.	27136	1.28	1.13	5.73	Corsi et al., 1997	20
WI, Driftless area	Steep slopes. A lot of forage and pasture. 99% ag.	5952	1.45	0.72	2.19	Corsi et al., 1997	7
WI, Driftless area	Steep slopes. A lot of forage and pasture. 100% ag	6144	1.50	0.38	6.19	Corsi et al., 1997	16
WI, N. Cent. forest	Moraines, sandy outwash. 92% ag, 8% forest.	2688	1.55	0.60	2.50	Corsi et al., 1997	6
WI, Driftless area	Steep slopes. A lot of forage and pasture. 100% ag	3456	1.89	1.06	2.73	Corsi et al., 1997	19
WI, Driftless area	Steep slopes. A lot of forage and pasture. 100% ag	1792	2.05	0.85	0.32	Corsi et al., 1997	18
WI, Driftless area	Steep slopes. A lot of forage and pasture. 100% ag	9600	2.38	1.17	3.58	Corsi et al., 1997	17
Dane County, WI	Dairy. 90% ag.	256	0.68			Panuska and Lillie, 1995	4
Southeast WI	Dairy and specialty crops. Irregular moraines. 93% ag.	26304	0.49	0.26	0.72	Panuska and Lillie, 1995	5
Southeast WI	Dairy and specialty crops. Irregular moraines. 94% ag.	8128	0.76			Panuska and Lillie, 1995	6
Southeast WI	Dairy and specialty crops. Irregular moraines. 95% ag.	15616	0.47	0.29	0.65	Panuska and Lillie, 1995	7
Southeast WI	Dairy and specialty crops. Irregular moraines. 72% ag.	13939	0.49	0.48	0.50	Panuska and Lillie, 1995	31
WI, N. Cent. forest	Moraines, sandy outwash. 84% ag, 13% water.	813	0.68			Panuska and Lillie, 1995	34

Treynor, IA	Corn, conventional tillage, terracing.	60	0.22	0.02	0.54	Alberts et al., 1978
Treynor, IA	Corn, conventional tillage, contour farming	33.6	0.41	0.07	1.15	Alberts et al., 1978
Treynor, IA	Corn, conventional tillage, contour farming	30	0.62	0.08	1.89	Alberts et al., 1978
Pottawattamie County, IA	Corn, conventional tillage, contour farming	33.6	0.86	0.53	1.18	Burwell et al., 1975
Eastern SD	Alfalfa, bromegrass pasture	4.1	0.09			Harms et al., 1974
Eastern SD	Pasture	6.3	0.22			Harms et al., 1974
Coshocton, OH	Kentucky Bluegrass, Orchardgrass, Rotationally Grazed		0.09			Owens et al. 2003
Coshocton, OH	Kentucky Bluegrass, Orchardgrass, Rotationally Grazed		0.15			Owens et al. 2003
Coshocton, OH	Kentucky Bluegrass, Orchardgrass. Summer grazed, winter feeding lot.		0.89			Owens et al. 2003
Coshocton, OH	Kentucky Bluegrass, Orchardgrass. Summer grazed, winter feeding lot.		1.66			Owens et al. 2003
Treynor, IA	Bromegrass, rotationally grazed	43	0.25	0.07	0.45	Schuman et al., 1973
Knox County, MO	Soybeans, No Till, contour farming, waterway	4.44	0.31	0.27	0.36	Udawatta et al., 2004
Knox County, MO	Soybeans No Till, waterway	4.44	1.16	0.45	2.31	Udawatta et al., 2004
Knox County, MO	Corn No Till, waterway	4.44	1.47	0.27	3.20	Udawatta et al., 2004
Knox County, MO	Corn No Till, contour farming, waterway	4.44	1.60	1.51	1.78	Udawatta et al., 2004
Knox County, MO	2 yr corn-soybean rotation. Conservation tillage, waterway.	1.65	0.89			Udawatta et al., 2002
Knox County, MO	2 yr corn-soybean rotation. Conservation tillage, waterway.	3.16	0.98			Udawatta et al., 2002
Chickasha, OK	Wheat	5.3	1.42	0.53	3.82	Reckhow et al., 1980
Swift Current, Saskatchewan	Spring wheat, summer stubble, 2-yr rotation	5	0.31	0.09	0.53	Reckhow et al., 1980
	Spring wheat, summerfallow	5	1.20	0.36	2.05	Reckhow et al., 1980
	Spring wheat, fall fertilized summerfallow	5	2.58	0.18	4.98	Reckhow et al., 1980
Coshocton, OH	Winter grazed, summer rotational, orchardgrass and bluegrass cover	1	3.20			Reckhow et al., 1980
Coshocton, OH	Summer grazed	1	0.76			Reckhow et al., 1980
Chickasha, OK	Continuous grazing, little bluestem cover, active gullies	11.1	1.30	0.24	3.44	Reckhow et al., 1980
Rhode River Watershed, MD	Continuous grazing with some supplementary winter feeding, some hay production	351.2	3.38			Reckhow et al., 1980
Chickasha, OK	Rotation grazing little bluestem cover, good cover	11	0.22	0.02	1.28	Reckhow et al., 1980
Chickasha, OK	Continuous grazing	7.8	4.36			Olness et al., 1980
Chickasha, OK	Continuous grazing	11.1	0.68			Olness et al., 1980
Chickasha, OK	Rotationally grazed pasture	9.6	2.75			Olness et al., 1980
Chickasha, OK	Rotationally grazed pasture	11	0.18			Olness et al., 1980

Response of Processing Potato Varieties to Nitrogen and Enhanced Efficiency Fertilizers
-2008-

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Summary: A field experiment was conducted at the Sand Plain Research Farm in Becker, Minn. to evaluate the effects of nitrogen rate, source and timing on yield and quality of four processing potato varieties/selections: Russet Burbank, Umatilla, Premier, and AOND95249-1Rus, a selection from NDSU potato breeding program. Ten N treatments were evaluated. Six of the ten treatments were conventional N sources with the following N rates (lb/A): 30, 120, 180, 240 (early), 240 (late) and 300. Four of the ten treatments were ESN: 180 and 240 lb N/A preplant and 180 and 240 lb N/A at emergence. A starter N rate of 30 lb N/A as monoammonium phosphate was included in the total N rate applied. Release of N from ESN tended to be 20-30 days faster than that recorded in previous years, suggesting that the coating was either different or perhaps damaged. In general, marketable and total yields of all varieties increased with increasing N rate with optimum yield between 180 and 240 lb N/A depending on timing and source. For conventional N at the 240 lb N/A rate more up front N was optimum for Russet Burbank, Premier, and AOND95249-1Rus, while late season N was optimum for Umatilla. Except for Umatilla, yields with ESN applied preplant were generally higher than with ESN applied at emergence. For Umatilla, yields with ESN applied at emergence tended to be higher than those with ESN applied preplant, which is consistent with late season N response with conventional N sources. Russet Burbank and Premier tended to be the highest yielding varieties followed by AOND95249-1Rus and then Umatilla. Premier, AOND95249-1Rus, and Umatilla all had fewer misshaped potatoes than Russet Burbank with AOND95249-1Rus having the fewest #2 potatoes. Tubers greater than 6 and 10 oz were highest for AOND95249-1Rus and lowest for Umatilla. Hollow heart incidence was highest in Russet Burbank followed by Premier, AOND95249-1Rus and then Umatilla. Specific gravity was highest in AOND95249-1Rus followed by Premier, Umatilla and then Russet Burbank. Chip color was darkest for Russet Burbank. Stem and bud end glucose concentrations were highest for Russet Burbank followed by Umatilla, Premier, and then AOND95249-1Rus.

Studies with ESN, a controlled release N fertilizer, have been conducted for the past four years using only 'Russet Burbank' as the test cultivar. The main findings have shown that the fertilizer can be used as a substitute for many split applications of UAN with fertigation. There is strong interest in evaluating new cultivars such as 'Umatilla', 'Preimer' from the northwest breeding program and a new selection, AOND95249-1Rus, from the NDSU breeding program that produce better quality potatoes. Specific advantages of the new cultivars/selection include better tuber uniformity and less susceptibility to sugar ends. The best results with ESN indicate an early sidedress application provides the best yield and quality. However, there is interest in using ESN as a preplant fertilizer. In previous studies, use of ESN shows the greatest advantage of reducing nitrate leaching when excessive rainfall occurs in May and June. Because the release characteristics of ESN can affect tuber set and bulking of potatoes, evaluation this new technology is essential for adoption. The use of newer cultivars in combination with newer cost effective urea coated fertilizer technology has the potential to greatly improve N use efficiency in potato and reduce nitrate losses. Research over different growing seasons is needed to evaluate the N response and use efficiency characteristics of new cultivars in comparison with Russet Burbank, as well as to estimate an N budget (inputs vs. outputs). These data will be useful for growers to more efficiently manage N for these cultivars.

The overall goal of this research is to optimize N fertilizer management for new processing potato cultivars under Minnesota growing conditions. Specific objectives include: a) Determine the effect of N rate and source on tuber yield and quality of new cultivars/selections potato cultivars and b) Evaluate the effectiveness of a cost-effective coated urea product on tuber yield and quality of the potato cultivars/selections. This is the first year of a three year study.

Materials and Methods

This study was conducted at the Sand Plain Research Farm in Becker, Minnesota on a Hubbard loamy sand soil. . The previous crop was rye, followed by a mustard green manure that was plowed down in the fall of 2007. Selected soil chemical properties before planting were as follows (0-6"): pH, 6.4; organic matter, 2.0%; Bray P1, 33 ppm; ammonium acetate extractable K, Ca, and Mg, 124, 766, and 143 ppm, respectively; hot water extractable B, 0.2 ppm; Ca-phosphate extractable SO_4-S, 1.5 ppm; and DTPA extractable Zn, Cu, Fe, and Mn, 1.2, 0.5, 23.2, and 5.9 ppm, respectively. Extractable nitrate-N and ammonium-N in the top 2 ft of soil were 17.8 and 16.8 lb/A, respectively.

Four, 23-ft rows were planted for each plot with the middle two rows used for sampling and harvest. Cut "A" Russet Burbank, Umatilla, Premier, and AOND95249-1Rus seed were hand planted in furrows on May 8, 2008. The Umatilla, Premier, and AOND95249-1Rus seed were treated with NuBark, while the Russet Burbank seed was untreated. Row spacing was 12 inches within each row and 36 inches between rows. Each treatment was replicated four times for each variety in a randomized complete block design. Admire Pro was applied in-furrow for beetle control, along with the systemic fungicides Moncut 70DF and Ultra Flourish. Weeds, diseases, and other insects were controlled using standard practices. Rainfall was supplemented with sprinkler irrigation using the checkbook method of irrigation scheduling.

Each cultivar was subjected to 10 N treatments with different N sources, rates, and application timing as described in Table 1 below. A complete factorial arrangement was used with cultivar and N treatment as main effects.

Preplant ESN fertilizer was applied 9 days before planting on April 28 and disked in. The 30-lb N/A application at planting as MAP was banded 3 inches to each side and 2 inches below the seed piece using a belt type applicator. For all treatments, banded fertilizer at planting included 130 lb P_2O_5/A as monommonium phosphate or triple superphosphate (for the 0 N control), 180 lb K_2O/A as potassium chloride and potassium magnesium sulfate, and 20 lb Mg/A and 45 lb S/A as potassium magnesium sulfate. Emergence N applications were supplied as urea and mechanically incorporated during hilling. Post-hilling N was applied by hand as 50% granular urea-N and 50% ammonium nitrate-N, which was watered-in with overhead irrigation to simulate fertigation with a 28% UAN solution. Emergence fertilizer was applied on May 21 and post-hilling N was applied on June 13, June 23, July 7, and July 21.

A WatchDog weather station from Spectrum Technologies was used to monitor rainfall, air temperature, and soil temperature at the fertilizer band depth. Measured amounts of ESN fertilizer were placed in plastic mesh bags, buried at the depth of fertilizer placement both at the time of preplant application and at emergence, and removed at regular intervals to track N release over time. Plant stands were measured on June 19 and the number of stems per plant was counted on June 24. Tuber set was measured June 30 (for 3 blocks) and July 1 (for the 4th block). Petiole samples were collected from the 4th leaf from the terminal on three dates: June 25, July 9, and July 29. Petioles were analyzed for nitrate-N on a dry weight basis.

Table 1. Nitrogen treatments tested on processing potato varieties.

Treatment	Preplant	Planting	Emergence	Post-hilling**	Total
	------------------------ N sources* and rates (lb N/A) ------------------------				
1	0	0	0	0	0
2	0	30 MAP	50 Urea	10 UAN x 4	120
3	0	30 MAP	70 Urea	15 UAN x 4	180
4	0	30 MAP	90 Urea	30 UAN x 4	240
5	0	30 MAP	50 Urea	40 UAN x 4	240
6	0	30 MAP	90 Urea	45 UAN x 4	300
7	150 ESN	30 MAP	0	0	180
8	210 ESN	30 MAP	0	0	240
9	0	30 MAP	140 ESN	0	180
10	0	30 MAP	200 ESN	0	240

*ESN = Environmentally Smart Nitrogen (44-0-0), MAP = monoammonium phosphate urea = 46-0-0, UAN = a combination of granular urea and ammonium nitrate.
**Post-hilling N was applied 4 times at 10-14 day intervals.

Vines were harvested on Sept 24 (from 3 blocks) and Sept 26 (from the 4th block) from two, 10-ft sections of row, followed by mechanically beating the vines over the entire plot area. Plots were machine harvested on Sept 30 and total tuber yield and graded yield were measured. Sub-samples of vines and tubers were collected to determine moisture percentage and N concentrations, which were then used to calculate N uptake and distribution within the plant (Note: all the data for N uptake were not available at the time of this report and therefore will be presented at a later time). Tuber sub-samples were also used to determine tuber specific gravity and the incidence of hollow heart and brown center. Stem and bud end sugar contents after frying were determined after harvest. Additional fry tests will be made after six months of storage at about 45 F.

RESULTS

Weather

Rainfall and irrigation for the 2008 growing season are provided in Figure 1. From April 20 to Sept 23, approximately 20 inches of rainfall was supplemented with 13 inches of irrigation. In general, there were many small leaching events throughout the season, with one large event near the end of the growing season. Leaching events (greater than 1 inch of water) occurred at 10, 26, 37, 43 and 126 days after planting. Air and soil temperature measurements are provided in Figure 2.

Nitrogen Release from ESN

Figure 3 shows release of N from ESN applied preplant and at emergence. Release of N from ESN tended to be faster than that recorded in previous years. In 2007, approximately 90% of N was released by 80 days after planting for preplanted fertilizer and by 90 days after planting for ESN applied at planting and emergence. In 2008, 90% has been released by 50 days after planting for the preplant application and by about 60 days for the emergence application. Given the later planting date in 2008 compared with 2007, the shorter release time may have been advantageous. It is unclear why release rates were faster in 2008 as soil temperatures were actually cooler early in the season than in 2007.

Tuber Yield

Nitrogen rate, source, and timing comparisons

Tables 2-5 show the effects of N application rate, source, and timing on tuber yield and size distribution for the four processing varieties. For Russet Burbank (Table 2), marketable and total yields increased with increasing N rate with optimum yield between 180 and 240 lb N/A depending on timing and source. Numerically highest total, marketable and #1 yields were with ESN applied preplant at the 240 lb N/A rate. Yields with preplant ESN tended to be higher than those with emergence applied ESN. Within conventional N sources at the 240 lb N/A rate, N applied earlier (treatment 4) tended to result in higher yields than N applied later in the season (treatment 5), although differences were not statistically significant. At equivalent N rates, N source did not significantly affect yield. For Umatilla (Table 3), marketable and total yields increased with increasing N rate with optimum yield at about 240 lb N/A depending on timing and source. Numerically highest marketable yields were with conventional N applied later in the season at the 240 lb N/A rate and ESN applied at emergence at the same rate. Within conventional N sources at the 240 lb N/A rate, N applied later (treatment 5) resulted in higher yields than N applied earlier in the season (treatment 4). ESN applied at emergence tended to result in higher yields than ESN applied preplant, which is consistent with the late season N response with conventional sources. At equivalent N rates, N source did not significantly affect yield, except for ESN applied at emergence (treatment 10) resulted in higher yields than conventional N applied upfront (treatment 4). For Premier, (Table 4), marketable and total yields increased with increasing N rate with optimum yield between 180 and 240 lb N/A depending on timing and source. Numerically highest total, marketable and #1 yields were with ESN applied preplant at the 180 lb N/A rate. Yields with preplant ESN tended to be higher than those with emergence applied ESN at the 180 lb N/A rate, but no differences due to timing were observed at the 240 lb N/A rate with ESN. Within conventional N sources at the 240 lb N/A rate, N applied earlier (treatment 4) tended to result in higher yields than N applied later in the season (treatment 5), although differences were not statistically significant. At equivalent N rates, N source did not significantly affect marketable yield. For AOND95249-1Rus (Table 5), marketable and total yields increased with increasing N rate with optimum yield between 180 and 240 lb N/A depending on timing and source. Numerically highest total, marketable and #1 yields were with ESN applied preplant at the 180 or 240lb N/A rates. Yields with preplant ESN tended to be higher than those with emergence applied ESN. Within conventional N sources at the 240 lb N/A rate, N applied earlier (treatment 4) tended to result in higher yields than N applied later in the season (treatment 5), although differences were not statistically significant. At the 240 lb N/A, N source did not significantly affect yield, but at the 180 lb N/A rate, ESN applied preplant resulted in higher yields than conventional N and ESN applied at emergence.

General varietal comparisons

Russet Burbank and Premier tended to be the highest yielding varieties followed by AOND95249-1Rus and then Umatilla. Premier, AOND95249-1Rus, and Umatilla all had fewer misshaped potatoes than Russet Burbank with AOND95249-1Rus having the fewest #2 potatoes. Tubers greater than 6 and 10 oz were highest for AOND95249-1Rus and lowest for Umatilla.

Stand Count, Stem Number and Tuber Quality

Nitrogen rate, source, and timing comparisons

Tables 6-9 show the effects of N application rate, source, and timing on stand count, stems per plant hollow heart, specific gravity and frying quality for the four processing varieties. For Russet Burbank (Table 6), stand ranged from 97 to 100% and was not affected by treatment. Stems per plant ranged from 3.1 to 4.3 per plant and was not affected by treatment. Incidence of hollow heart was quite high ranging from 10 to 26% with inconsistent effects of N treatment. The control treatment had a high incidence while ESN applied preplant at 180 lb N/A had the lowest incidence. Late season applied N (treatment 5) resulted in the highest incidence of hollow heart. Specific gravity was not affected by treatment and generally high for all treatments. Chip color, AGT score, stem and bud sucrose were not affected by treatment. Stem and bud end glucose were affected by treatment. Increasing N rate tended to decrease glucose in the stem and bud ends. Late season N (treatment 5) tended to increase stem and bud glucose compared with early season N (treatment 4). For Umatilla (Table 7), stand ranged from 93 to 99% and was not affected by treatment. Stems per plant ranged form 3.1 to 4.5 per plant and was affected by treatment, but not consistently by N rate, source or timing. Reasons for the effects on stem count are not clear. Incidence of hollow heart was quite low ranging from 0 to 10% with inconsistent effects of N treatment. ESN applied preplant at 180 lb N/A resulted in a 10% hollow heart incidence, while there was no hollow heart with the other three ESN treatments. Specific gravity was not affected by treatment and generally high for all treatments. Chip color, AGT score, stem and bud end sucrose, and stem end glucose were not affected by treatment. Bud end glucose was affected by treatment with the early season N (treatment 4) resulting in the highest glucose concentrations. Premier (Table 8), stand ranged from 97 to 100% and was not affected by treatment. Stems per plant ranged form 3.9 to 4.5 per plant and was not affected by treatment. Incidence of hollow heart ranged from 5 to 16% and was not significantly affected by treatment. Specific gravity was not affected by treatment and generally high for all treatments. Frying quality was also not affected by treatment. For AOND95249-1Rus (Table 9), stand ranged from 83% to 93% and was not affected by treatment. Stems per plant ranged form 1.9 to 2.4 per plant and was not affected by treatment. Incidence of hollow heart was ranged from 3 to 9% and was not affected by treatment. Specific gravity was quite high. Highest specific gravity was in the control plots while lowest specific gravity was found in early season conventional N plots (treatment 4). Chip color, and stem and bud end glucose were not affected by treatment. AGT score and stem and bud end sucrose were affected by treatment, but were not consistently related to N rate, timing, or source.

General varietal comparisons

AOND95249-1Rus tended to have the lowest stand count and lowest number of stems per plant than the other varieties, which may have resulted in larger tubers. This selection likely has fewer eyes per tuber, which could result in more blanks and fewer stems per plant. Hollow heart incidence was highest in Russet Burbank followed by Premier, AOND95249-1Rus and then Umatilla. Specific gravity was highest in AOND95249-1Rus followed by Premier, Umatilla and then Russet Burbank. Chip color was darkest for Russet Burbank. Stem and bud end glucose concentrations were highest for Russet Burbank followed by Umatilla, Premier, and then AOND95249-1Rus.

Petiole Nitrate-N Concentrations

Nitrogen rate, source, and timing comparisons

Petiole NO_3-N concentrations on three dates as affected by N rate, N source, and N timing are presented in Tables 10-13. As expected, petiole NO_3-N generally increased with increasing N rate for all varieties and decreased as the season progressed. Petiole NO_3-N levels with the 300 lb N/A rate applied at planting were generally the highest of any treatment, especially later in the season, and may explain the decrease in yield at this rate compared with lower rates if they stimulated vine growth at the expense of tuber bulking.

Differences between urea and ESN treatments were significant throughout the sampling dates, but the differences depended on the time of the season. In contrast to previous years, petiole NO_3-N was significantly higher with ESN than with urea on the first sampling date and lower than urea on the last sampling date. In previous years, ESN was usually lower than urea on the first sampling data and higher than urea on the last sampling date. These results are consistent with the quicker release pattern observed for ESN early in the growing season. The fertilizer used in 2008 was farmer grade ESN, which may have more cracks in the coating than the research grade that we have used in the past. The cracks in the coating would likely cause a quicker release regardless of temperature.

General varietal comparisons

At the June 25 sampling date, petiole nitrate levels were higher for Umatilla and AOND95249-1Rus than Russet Burbank and Premier. Difference became less distinct towards the July 29 sampling date. Based on yield responses to N, petiole nitrate levels should be higher for Umatilla early in the growing season and during later bulking stages than for the other varieties. Further research is needed to determine more precise levels required for this variety in the Midwest.

CONCLUSIONS

Release of N from ESN was 20-30 days faster than that recorded in previous years, suggesting that the coating was either different or perhaps damaged. In general, marketable and total yields of all varieties increased with increasing N rate with optimum yield between 180 and 240 lb N/A depending on timing and source. For conventional N at the 240 lb N/A rate more up front N was optimum for Russet Burbank, Premier, and AOND95249-1Rus, while late season N was optimum for Umatilla. Except for Umatilla, yields with ESN applied preplant were generally higher than with ESN applied at emergence. For Umatilla, yields tended to be higher with ESN applied at emergence that with ESN applied preplant, which is consistent with the late season N response with conventional sources. Russet Burbank and Premier tended to be the highest yielding varieties followed by AOND95249-1Rus and then Umatilla. Premier, AOND95249-1Rus, and Umatilla all had fewer misshaped potatoes than Russet Burbank with AOND95249-1Rus having the fewest #2 potatoes. Tubers greater than 6 and 10 oz were highest for AOND95249-1Rus and lowest for Umatilla. Hollow heart incidence was highest in Russet Burbank followed by Premier, AOND95249-1Rus and then Umatilla. Specific gravity was highest in AOND95249-1Rus followed by Premier, Umatilla and then Russet Burbank. Chip color was darkest for Russet Burbank. Stem and bud end glucose concentrations were highest for Russet Burbank followed by Umatilla, Premier and then AOND95249-1Rus.

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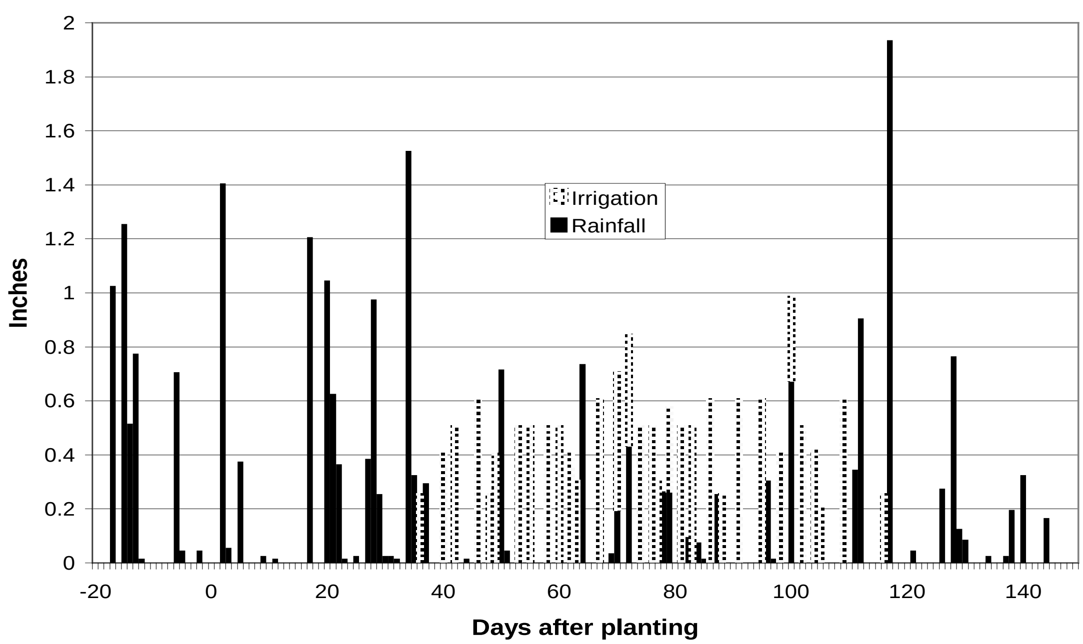

Figure 1. Rainfall and irrigation over the 2008 growing season.

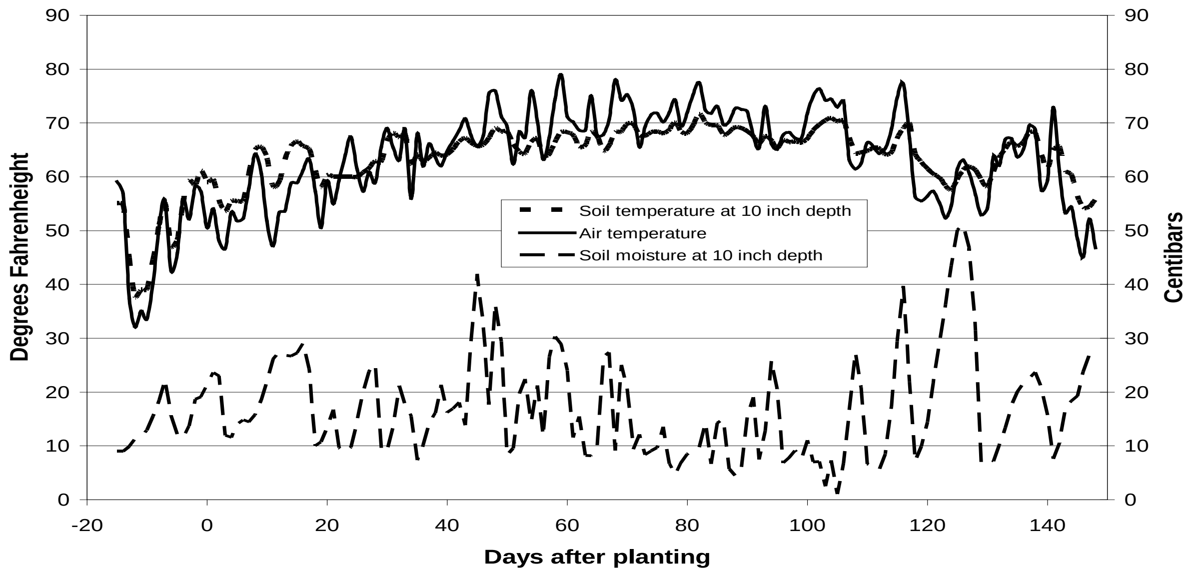

Figure 2. Average daily air and soil temperature and moisture at 10 inch depth below the top of the hill over the growing season.

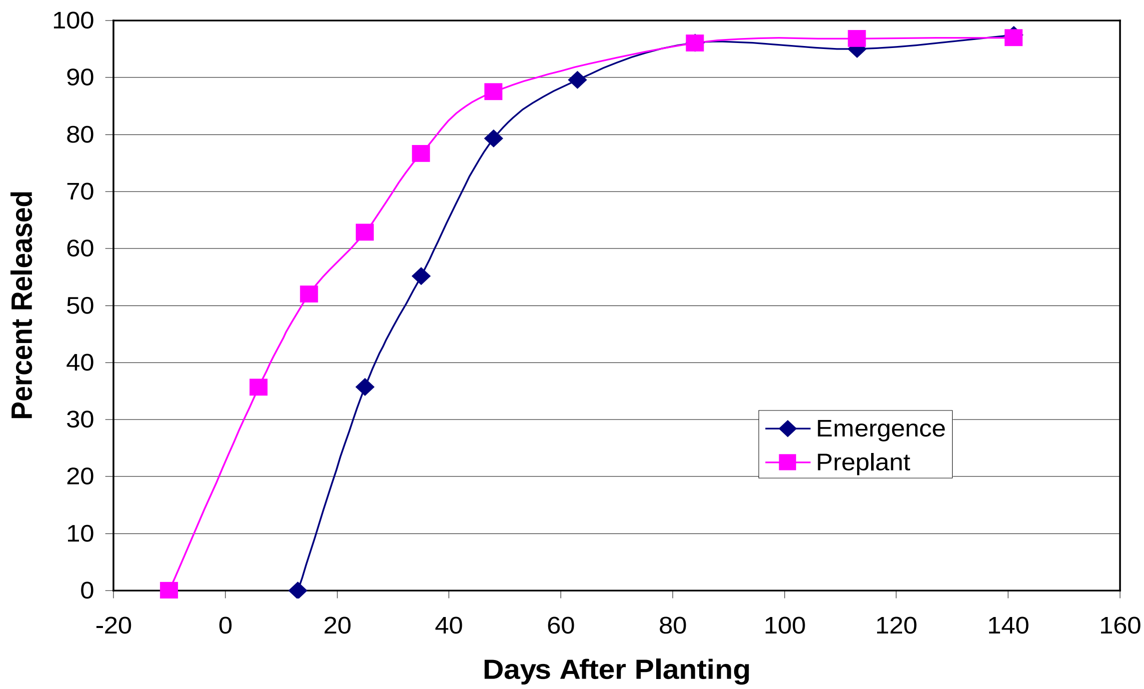

Figure 3. N released from ESN applied preplant and at emergence in 2008.

Table 2. Effect of N rate, source, and timing on Russet Burbank tuber yield and size distribution.

Nitrogen Treatments				Tuber Yield										
Trtmt #	N Source	N Rate	N Timing[1]	0-4 oz	4-6 oz	6-10 oz	10-14 oz	> 14 oz	Total	#1 > 4 oz	# 2 > 4 oz	Total marketable	> 6 oz	> 10 oz
		lb N / A	PP, P, E, PH	---------- cwt / A ----------									---------- % ----------	
1	control	30	0, 30, 0, 0	96.5	213.1	195.6	63.1	18.9	587.2	215.6	275.1	490.6	47.3	14.0
2	urea	120	0, 30, 50, 40	83.0	156.3	278.2	88.3	37.4	643.1	386.7	173.4	560.2	62.6	19.4
3	urea	180	0, 30, 70, 60	72.7	133.1	316.3	128.7	45.6	696.3	506.4	117.2	623.6	70.4	25.1
4	urea	240	0, 30, 90, 120	82.8	126.1	295.8	147.6	43.7	695.8	532.0	81.1	613.1	69.8	27.3
5	urea	240	0, 30, 50, 160	72.0	97.7	265.9	158.5	73.9	668.0	494.2	101.9	596.0	74.5	34.7
6	urea	300	0, 30, 90, 180	86.0	101.0	258.3	154.9	62.9	663.1	460.8	116.3	577.1	71.9	32.9
7	ESN	180	150, 30, 0, 0	88.4	194.1	309.8	75.8	21.4	689.5	490.8	110.3	601.1	59.1	14.2
8	ESN	240	210, 30, 0, 0	66.5	127.6	322.1	125.9	58.8	700.8	553.3	81.1	634.4	72.3	26.4
9	ESN	180	0, 30, 150, 0	68.9	127.0	288.6	123.4	50.0	657.8	454.7	134.2	589.0	70.3	26.4
10	ESN	240	0, 30, 210, 0	80.0	115.9	314.5	125.1	33.2	668.7	529.9	58.8	588.7	70.7	23.7
			Significance[2]	NS	**	**	**	*	**	**	**	**	**	**
			LSD (0.10)	---	35.3	38.6	39.0	31.3	35.4	52.7	36.3	40.5	8.0	8.5

[1]PP, P, E, PH = Preplant, Planting, Emergence, and Post-Hilling, respectively; 4 post-hilling applications were as follows: 20%, 20%, 30%, 30%.

[2]NS = Non-significant; ++, *, ** = Significant at 10%, 5%, and 1%, respectively.

Table 3. Effect of N rate, source, and timing on Umatilla tuber yield and size distribution.

Nitrogen Treatments				Tuber Yield										
Trtmt #	N Source	N Rate	N Timing[1]	0-4 oz	4-6 oz	6-10 oz	10-14 oz	> 14 oz	Total	#1 > 4 oz	# 2 > 4 oz	Total marketable	> 6 oz	> 10 oz
		lb N / A	PP, P, E, PH	---------- cwt / A ----------									---------- % ----------	
1	control	30	0, 30, 0, 0	126.1	124.8	176.6	17.5	3.7	448.5	309.4	13.1	322.5	44.1	4.8
2	Urea	120	0, 30, 50, 40	135.5	167.0	207.2	30.1	8.4	548.2	395.6	17.0	412.6	44.7	6.9
3	Urea	180	0, 30, 70, 60	133.1	147.6	251.4	46.1	8.7	586.9	442.5	11.3	453.8	52.2	9.3
4	Urea	240	0, 30, 90, 120	135.8	135.9	254.3	61.9	25.5	613.5	457.8	19.9	477.6	55.6	14.2
5	Urea	240	0, 30, 50, 160	112.9	138.7	281.7	73.7	26.4	633.4	480.5	40.1	520.5	60.3	15.9
6	Urea	300	0, 30, 90, 180	135.2	158.7	253.6	68.5	25.5	641.5	488.6	17.7	506.3	54.1	14.6
7	ESN	180	150, 30, 0, 0	159.1	191.6	230.0	30.1	6.5	617.3	442.9	15.2	458.2	43.1	6.0
8	ESN	240	210, 30, 0, 0	143.1	176.5	259.7	47.2	27.7	654.1	494.5	16.6	511.1	51.2	11.4
9	ESN	180	0, 30, 150, 0	94.5	122.7	263.9	77.1	32.0	590.2	480.0	15.7	495.7	63.2	18.4
10	ESN	240	0, 30, 210, 0	92.9	138.0	258.4	106.6	28.1	624.0	503.4	27.7	531.1	63.0	21.7
			Significance[2]	**	**	**	**	**	**	**	*	**	**	**
			LSD (0.10)	16.6	20.1	34.2	19.9	14.8	35.5	42.5	13.2	41.8	5.2	4.3

[1]PP, P, E, PH = Preplant, Planting, Emergence, and Post-Hilling, respectively; 4 post-hilling applications were as follows: 20%, 20%, 30%, 30%.

[2]NS = Non-significant; ++, *, ** = Significant at 10%, 5%, and 1%, respectively.

Table 4. Effect of N rate, source, and timing on Premier tuber yield and size distribution.

Nitrogen Treatments				Tuber Yield										
Trtmt #	N Source	N Rate	N Timing[1]	0-4 oz	4-6 oz	6-10 oz	10-14 oz	> 14 oz	Total	#1 > 4 oz	# 2 > 4 oz	Total marketable	> 6 oz	> 10 oz
		lb N / A	PP, P, E, PH	----- cwt / A -----									----- % -----	
1	control	30	0, 30, 0, 0	46.8	86.2	252.6	83.5	14.7	483.8	419.0	17.9	437.0	72.4	20.3
2	Urea	120	0, 30, 50, 40	51.5	110.8	286.4	106.8	29.5	585.1	510.9	22.7	533.6	72.3	23.4
3	Urea	180	0, 30, 70, 60	58.1	107.8	304.4	136.9	31.1	638.3	552.4	27.8	580.2	73.9	26.1
4	Urea	240	0, 30, 90, 120	55.2	91.2	292.1	146.8	64.1	649.3	570.7	23.4	594.1	77.4	32.5
5	Urea	240	0, 30, 50, 160	43.4	75.1	270.2	159.2	69.8	617.7	529.2	45.1	574.3	80.8	37.1
6	Urea	300	0, 30, 90, 180	52.0	86.3	279.5	155.9	73.5	647.3	558.1	37.2	595.3	78.8	35.5
7	ESN	180	150, 30, 0, 0	50.9	119.4	311.1	144.8	36.2	662.3	591.2	20.2	611.4	74.0	27.0
8	ESN	240	210, 30, 0, 0	43.9	77.3	274.6	166.4	85.5	647.6	574.5	29.2	603.7	81.3	39.0
9	ESN	180	0, 30, 150, 0	44.9	73.3	289.2	158.3	60.2	625.9	558.3	22.8	581.0	81.1	34.9
10	ESN	240	0, 30, 210, 0	52.7	85.6	279.5	166.8	62.8	647.5	577.0	17.8	594.8	78.5	35.4
Significance[2]				NS	*	NS	**	**	**	**	++	**	*	**
LSD (0.10)				---	26.1	---	37.2	26.3	37.6	40.9	18.2	39.4	6.3	7.2

[1]PP, P, E, PH = Preplant, Planting, Emergence, and Post-Hilling, respectively; 4 post-hilling applications were as follows: 20%, 20%, 30%, 30%.

[2]NS = Non-significant; ++, *, ** = Significant at 10%, 5%, and 1%, respectively.

Table 5. Effect of N rate, source, and timing on AOND95249-1Rus tuber yield and size distribution.

Nitrogen Treatments				Tuber Yield										
Trtmt #	N Source	N Rate	N Timing[1]	0-4 oz	4-6 oz	6-10 oz	10-14 oz	> 14 oz	Total	#1 > 4 oz	# 2 > 4 oz	Total marketable	> 6 oz	> 10 oz
		lb N / A	PP, P, E, PH	----- cwt / A -----									----- % -----	
1	control	30	0, 30, 0, 0	22.7	71.5	230.5	54.0	19.9	398.5	372.8	3.0	375.8	76.1	18.0
2	urea	120	0, 30, 50, 40	14.6	70.1	253.7	113.0	38.6	490.1	474.9	0.6	475.5	82.7	30.9
3	urea	180	0, 30, 70, 60	20.2	74.4	284.0	96.8	40.4	515.7	494.2	1.3	495.5	81.8	26.9
4	urea	240	0, 30, 90, 120	22.1	58.0	249.1	139.1	85.9	554.2	529.6	2.5	532.1	85.6	40.5
5	urea	240	0, 30, 50, 160	19.1	59.5	221.8	138.1	105.5	544.0	520.6	4.2	524.9	85.6	44.8
6	urea	300	0, 30, 90, 180	25.5	56.4	222.8	166.4	84.0	555.0	526.6	2.9	529.5	85.2	45.1
7	ESN	180	150, 30, 0, 0	22.5	78.1	261.3	137.3	83.9	583.0	557.4	3.1	560.5	82.8	38.1
8	ESN	240	210, 30, 0, 0	25.8	61.4	228.5	148.1	121.5	585.4	556.2	3.3	559.5	85.2	46.1
9	ESN	180	0, 30, 150, 0	16.0	57.4	269.8	130.7	59.1	533.0	514.8	2.2	517.0	86.3	35.9
10	ESN	240	0, 30, 210, 0	20.9	58.7	252.3	136.7	103.1	571.6	549.2	1.5	550.7	86.1	42.1
Significance[2]				++	NS	NS	**	**	**	**	NS	**	**	**
LSD (0.10)				9.1	---	---	22.4	42.7	32.8	30.6	---	32.3	4.2	10.0

[1]PP, P, E, PH = Preplant, Planting, Emergence, and Post-Hilling, respectively; 4 post-hilling applications were as follows: 20%, 20%, 30%, 30%.

[2]NS = Non-significant; ++, *, ** = Significant at 10%, 5%, and 1%, respectively.

Table 6. Effect of N rate, source, and timing on Russet Burbank stand count, stems per plant, and tuber quality.

Nitrogen Treatments				Tuber Quality		Frying Quality							
	N	N	N	Hollow	Specific	Chip	AGT	Stem		Bud			
Trtmt	Source	Rate	Timing[1]	Heart	Gravity	Color	Score	Sucrose	Glucose	Sucrose	Glucose	Stand	Stems
#		lb N / A	PP, P, E, PH	%								%	per Plant
1	control	30	0, 30, 0, 0	22.5	1.0821	3.0	50.5	0.454	8.172	2.229	0.730	97.9	3.65
2	urea	120	0, 30, 50, 40	16.9	1.0867	3.0	50.8	0.265	6.998	2.066	0.432	97.2	3.25
3	urea	180	0, 30, 70, 60	18.0	1.0895	2.5	53.5	0.298	4.840	1.693	0.372	99.3	3.70
4	urea	240	0, 30, 90, 120	15.0	1.0882	2.8	52.0	0.204	4.102	1.513	0.336	97.9	4.00
5	urea	240	0, 30, 50, 160	26.3	1.0873	3.0	52.8	0.269	5.033	1.886	0.469	97.9	4.00
6	urea	300	0, 30, 90, 180	19.0	1.0907	2.5	53.3	0.418	3.698	1.508	0.302	99.3	3.80
7	ESN	180	150, 30, 0, 0	10.0	1.0926	3.0	52.3	0.295	4.410	1.763	0.372	97.9	4.35
8	ESN	240	210, 30, 0, 0	19.8	1.0888	2.5	53.3	0.260	3.737	1.586	0.334	97.9	3.95
9	ESN	180	0, 30, 150, 0	21.3	1.0885	3.0	51.3	0.250	4.428	2.047	0.436	99.3	3.10
10	ESN	240	0, 30, 210, 0	13.2	1.0931	2.5	53.8	0.321	4.322	2.015	0.502	100.0	3.90
			Significance[2]	*	NS	NS	NS	NS	**	NS	*	NS	NS
			LSD (0.10)	8.6	---	---	---	---	1.493	---	0.235	---	---

[1]PP, P, E, PH = Preplant, Planting, Emergence, and Post-Hilling, respectively; 4 post-hilling applications were as follows: 20%, 20%, 30%, 30%.
[2]NS = Non-significant; ++, *, ** = Significant at 10%, 5%, and 1%, respectively.

Table 7. Effect of N rate, source, and timing on Umatilla stand count, stems per plant, and tuber quality.

Nitrogen Treatments				Tuber Quality		Frying Quality							
	N	N	N	Hollow	Specific	Chip	AGT	Stem		Bud			
Trtmt	Source	Rate	Timing[1]	Heart	Gravity	Color	Score	Sucrose	Glucose	Sucrose	Glucose	Stand	Stems
#		lb N / A	PP, P, E, PH	%								%	per Plant
1	control	30	0, 30, 0, 0	0.0	1.0919	2.8	52.8	0.864	1.505	1.602	0.292	95.1	4.00
2	urea	120	0, 30, 50, 40	1.0	1.0924	2.8	53.5	1.116	1.049	1.738	0.298	99.3	3.45
3	urea	180	0, 30, 70, 60	0.0	1.0949	2.5	54.5	0.962	1.191	1.824	0.289	97.2	4.15
4	urea	240	0, 30, 90, 120	1.0	1.0922	2.5	54.0	1.111	1.410	2.184	0.560	96.5	3.80
5	urea	240	0, 30, 50, 160	0.0	1.0939	2.0	55.8	1.160	1.050	1.603	0.294	97.9	3.35
6	urea	300	0, 30, 90, 180	2.0	1.0945	2.5	54.0	1.313	1.297	2.086	0.402	97.2	4.35
7	ESN	180	150, 30, 0, 0	10.0	1.0911	2.8	52.5	0.867	1.267	1.606	0.243	99.3	4.20
8	ESN	240	210, 30, 0, 0	0.0	1.0900	2.8	52.5	0.882	1.129	1.757	0.323	97.9	4.45
9	ESN	180	0, 30, 150, 0	0.0	1.0935	2.8	54.3	1.015	1.295	1.712	0.441	95.1	3.10
10	ESN	240	0, 30, 210, 0	0.0	1.0880	3.0	52.3	0.956	1.174	1.869	0.224	93.1	4.10
			Significance[2]	*	NS	NS	NS	NS	NS	NS	++	NS	*
			LSD (0.10)	5.8	---	---	---	---	---	---	0.223	---	0.71

[1]PP, P, E, PH = Preplant, Planting, Emergence, and Post-Hilling, respectively; 4 post-hilling applications were as follows: 20%, 20%, 30%, 30%.
[2]NS = Non-significant; ++, *, ** = Significant at 10%, 5%, and 1%, respectively.

Table 8. Effect of N rate, source, and timing on Premier stand count, stems per plant, and tuber quality.

Nitrogen Treatments				Tuber Quality		Frying Quality							
Trtmt #	N Source	N Rate lb N / A	N Timing[1] PP, P, E, PH	Hollow Heart %	Specific Gravity	Chip Color	AGT Score	Stem Sucrose	Stem Glucose	Bud Sucrose	Bud Glucose	Stand %	Stems per Plant
1	control	30	0, 30, 0, 0	6.0	1.0960	2.5	54.8	1.315	1.275	1.791	0.203	99.3	4.10
2	urea	120	0, 30, 50, 40	8.0	1.0940	2.5	57.8	1.284	1.183	1.696	0.158	99.3	4.15
3	urea	180	0, 30, 70, 60	7.0	1.0906	2.0	58.3	1.357	1.140	2.108	0.205	98.6	4.00
4	urea	240	0, 30, 90, 120	7.1	1.0911	2.0	56.5	1.432	0.838	2.102	0.188	98.6	4.45
5	urea	240	0, 30, 50, 160	5.0	1.0894	2.3	57.3	1.728	0.984	2.372	0.233	99.3	4.15
6	urea	300	0, 30, 90, 180	13.1	1.0918	2.3	56.0	1.754	0.730	2.435	0.235	97.9	4.20
7	ESN	180	150, 30, 0, 0	8.9	1.0974	2.0	58.8	1.230	0.861	1.928	0.247	100.0	4.25
8	ESN	240	210, 30, 0, 0	16.0	1.0897	2.3	55.3	1.493	0.783	2.177	0.189	97.2	4.30
9	ESN	180	0, 30, 150, 0	10.1	1.0915	2.0	56.5	1.384	1.006	2.262	0.255	99.3	3.90
10	ESN	240	0, 30, 210, 0	14.0	1.0914	2.3	57.5	1.413	0.630	1.777	0.270	100.0	4.35
			Significance[2]	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
			LSD (0.10)	---	---	---	---	---	---	---	---	---	---

[1]PP, P, E, PH = Preplant, Planting, Emergence, and Post-Hilling, respectively; 4 post-hilling applications were as follows: 20%, 20%, 30%, 30%.

[2]NS = Non-significant; ++, *, ** = Significant at 10%, 5%, and 1%, respectively.

Table 9. Effect of N rate, source, and timing on AOND95249-1Rus stand count, stems per plant, and tuber quality.

Nitrogen Treatments				Tuber Quality		Frying Quality							
Trtmt #	N Source	N Rate lb N / A	N Timing[1] PP, P, E, PH	Hollow Heart %	Specific Gravity	Chip Color	AGT Score	Stem Sucrose	Stem Glucose	Bud Sucrose	Bud Glucose	Stand %	Stems per Plant
1	control	30	0, 30, 0, 0	4.0	1.1117	2.0	56.5	1.859	0.534	2.000	0.234	91.7	2.05
2	urea	120	0, 30, 50, 40	5.0	1.1081	2.5	56.5	1.540	0.491	1.522	0.188	93.7	2.10
3	urea	180	0, 30, 70, 60	7.0	1.1093	2.0	57.0	1.624	0.510	1.716	0.171	87.5	2.40
4	urea	240	0, 30, 90, 120	9.0	1.0969	2.5	54.5	1.299	0.431	1.746	0.206	91.7	2.10
5	urea	240	0, 30, 50, 160	3.0	1.1069	2.3	55.5	1.392	0.347	1.972	0.255	92.4	2.25
6	urea	300	0, 30, 90, 180	5.0	1.1045	2.0	58.5	1.503	0.238	2.002	0.178	93.0	1.85
7	ESN	180	150, 30, 0, 0	6.0	1.1038	2.5	53.8	1.117	0.392	1.490	0.202	91.0	2.20
8	ESN	240	210, 30, 0, 0	9.0	1.1037	2.3	56.0	1.686	0.509	2.236	0.174	92.4	2.35
9	ESN	180	0, 30, 150, 0	9.0	1.1068	2.5	53.8	1.259	0.419	1.541	0.243	82.7	1.95
10	ESN	240	0, 30, 210, 0	9.0	1.1081	2.0	58.0	1.860	0.578	2.215	0.229	93.1	2.40
			Significance[2]	NS	**	NS	++	++	NS	*	NS	NS	NS
			LSD (0.10)	---	0.0033	---	3.5	0.530	---	0.495	---	---	---

[1]PP, P, E, PH = Preplant, Planting, Emergence, and Post-Hilling, respectively; 4 post-hilling applications were as follows: 20%, 20%, 30%, 30%.

[2]NS = Non-significant; ++, *, ** = Significant at 10%, 5%, and 1%, respectively.

Table 10. Effect of N rate, source, and timing on Russet Burbank petiole nitrate-N levels.

Nitrogen Treatments				NO_3-N, ppm		
Trtmt #	N Source	N Rate	N Timing[1]			
		lb N / A	PP, P, E, PH	June 25	July 9	July 29
1	control	30	0, 30, 0, 0	4378	852	673
2	urea	120	0, 30, 50, 40	12436	4669	1442
3	urea	180	0, 30, 70, 60	12330	8339	4034
4	urea	240	0, 30, 90, 120	16177	11619	8073
5	urea	240	0, 30, 50, 160	16926	12749	12248
6	urea	300	0, 30, 90, 180	19341	14868	13966
7	ESN	180	150, 30, 0, 0	19006	7826	3311
8	ESN	240	210, 30, 0, 0	21033	13528	4105
9	ESN	180	0, 30, 150, 0	17222	6010	2341
10	ESN	240	0, 30, 210, 0	18565	10802	3759
			Significance[2]	**	**	**
			LSD (0.10)	2346	1729	2500

[1]PP, P, E, PH = Preplant, Planting, Emergence, and Post-Hilling, respectively; 4 post-hilling applications were as follows: 20%, 20%, 30%, 30%.

[2]NS = Non-significant; ++, *, ** = Significant at 10%, 5%, and 1%, respectively.

Table 11. Effect of N rate, source, and timing on Umatilla petiole nitrate-N levels.

Nitrogen Treatments				NO_3-N, ppm		
Trtmt #	N Source	N Rate	N Timing[1]			
		lb N / A	PP, P, E, PH	June 25	July 9	July 29
1	control	30	0, 30, 0, 0	9897	1512	116
2	urea	120	0, 30, 50, 40	17481	7753	1254
3	urea	180	0, 30, 70, 60	18253	10112	2812
4	urea	240	0, 30, 90, 120	19190	13362	9060
5	urea	240	0, 30, 50, 160	18122	15342	16185
6	urea	300	0, 30, 90, 180	20856	15676	17424
7	ESN	180	150, 30, 0, 0	22513	8894	1318
8	ESN	240	210, 30, 0, 0	25214	14361	3282
9	ESN	180	0, 30, 150, 0	22448	12507	2113
10	ESN	240	0, 30, 210, 0	17482	9605	2794
			Significance[2]	**	**	**
			LSD (0.10)	5177	4604	2616

[1]PP, P, E, PH = Preplant, Planting, Emergence, and Post-Hilling, respectively; 4 post-hilling applications were as follows: 20%, 20%, 30%, 30%.

[2]NS = Non-significant; ++, *, ** = Significant at 10%, 5%, and 1%, respectively.

Table 12. Effect of N rate, source, and timing on Premier petiole nitrate-N levels.

Nitrogen Treatments				NO_3-N, ppm		
Trtmt #	N Source	N Rate	N Timing[1]			
		lb N / A	PP, P, E, PH	June 25	July 9	July 29
1	control	30	0, 30, 0, 0	8328	908	88
2	urea	120	0, 30, 50, 40	12614	4559	716
3	urea	180	0, 30, 70, 60	18497	9356	3356
4	urea	240	0, 30, 90, 120	22708	13525	7634
5	urea	240	0, 30, 50, 160	17781	14363	12716
6	urea	300	0, 30, 90, 180	19303	15671	14398
7	ESN	180	150, 30, 0, 0	24068	6800	1870
8	ESN	240	210, 30, 0, 0	27112	11782	5274
9	ESN	180	0, 30, 150, 0	22821	9825	1926
10	ESN	240	0, 30, 210, 0	21238	12901	2869
			Significance[2]	**	**	**
			LSD (0.10)	5202	2513	2759

[1]PP, P, E, PH = Preplant, Planting, Emergence, and Post-Hilling, respectively;
4 post-hilling applications were as follows: 20%, 20%, 30%, 30%.
[2]NS = Non-significant; ++, *, ** = Significant at 10%, 5%, and 1%, respectively.

Table 13. Effect of N rate, source, and timing on AOND95249-1 Rus petiole nitrate-N levels.

Nitrogen Treatments				NO_3-N, ppm		
Trtmt #	N Source	N Rate	N Timing[1]			
		lb N / A	PP, P, E, PH	June 25	July 9	July 29
1	control	30	0, 30, 0, 0	11858	4468	342
2	urea	120	0, 30, 50, 40	18120	8325	2730
3	urea	180	0, 30, 70, 60	18915	11129	4869
4	urea	240	0, 30, 90, 120	24204	17094	11394
5	urea	240	0, 30, 50, 160	21547	15486	13726
6	urea	300	0, 30, 90, 180	23648	19562	16056
7	ESN	180	150, 30, 0, 0	23776	11425	4740
8	ESN	240	210, 30, 0, 0	24763	18369	4259
9	ESN	180	0, 30, 150, 0	21772	13856	2838
10	ESN	240	0, 30, 210, 0	22751	18455	3817
			Significance[2]	**	**	**
			LSD (0.10)	2177	3035	1709

[1]PP, P, E, PH = Preplant, Planting, Emergence, and Post-Hilling, respectively;
4 post-hilling applications were as follows: 20%, 20%, 30%, 30%.
[2]NS = Non-significant; ++, *, ** = Significant at 10%, 5%, and 1%, respectively.

Response of Processing Potato Varieties to Nitrogen Source, Rate, and Timing -2009-

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Summary: A field experiment was conducted at the Sand Plain Research Farm in Becker, Minn. to evaluate the effects of nitrogen rate, source and timing on yield and quality of four processing russet potato varieties/selections: Russet Burbank, Umatilla Russet, Premier Russet, and Bannock Russet. Ten N treatments were evaluated. Six of the ten treatments were conventional N sources with the following N rates (lb/A): 30, 120, 180, 240 (early), 240 (late) and 300. Four of the ten treatments were ESN: 180 and 240 lb N/A preplant and 180 and 240 lb N/A at emergence. A starter N rate of 30 lb N/A as monoammonium phosphate was included in the total N rate applied. Release of N from ESN was similar to that recorded in 2008 and tended to be 20-30 days faster than that recorded prior to 2008, suggesting that the coating more abraded than in previous years. In general, marketable and total yields of all varieties increased with increasing N rate with optimum yield between 240 lb N/A and 300 lb N/A depending on timing and source. For conventional N at the 240 lb N/A rate, more up front N was optimum for all varieties. Unlike 2008 when Umatilla responded favorably to late season applied, Umatilla vines died back early in 2009 due to disease, which apparently prevented efficient use of late season applied N. Russet Burbank tended to be the highest yielding variety followed by Bannock and Premier, and then Umatilla. Premier, Bannock, and Umatilla all had fewer misshaped potatoes than Russet Burbank with Premier having the fewest #2 potatoes. Tubers greater than 6 and 10 oz were highest for Premier followed by Bannock, Russet Burbank and then Umatilla. Hollow heart incidence was highest in Bannock, followed by Premier, Russet Burbank, and then Umatilla. Surface scab incidence was highest with Umatilla, followed by Russet Burbank and then Bannock and Premier. Specific gravity was highest in Russet Burbank and Umatilla, followed by Premier, and then Bannock. Stem and bud end chip color was darkest for Russet Burbank and lowest for Premier. AGT scores were highest for Premier and lowest for Russet Burbank. Stem end glucose concentrations were highest for Russet Burbank followed by Bannock, and then Premier and Umatilla.

Background: Studies with ESN, a controlled release N fertilizer, have been conducted for a number of years using 'Russet Burbank' as the test cultivar. The main findings have shown that the fertilizer can be used as a substitute for many split applications of UAN with fertigation. In 2008, a study was initiated to evaluate this product as well as characterize N response of some of the newer cultivars available for processing. The cultivars evaluated in 2008 included: 'Umatilla Russet', 'Premier Russet' from the northwest breeding program and a new selection, AOND95249-1Rus, from the NDSU breeding program. In addition, 'Russet Burbank' was included as the conventional cultivar. In 2009, 'Russet Burbank', 'Umatilla Russet', 'Premier Russet' and Bannock Russet (also from the Northwest breeding program) were evaluated. Specific advantages of the new cultivars/selections include better tuber uniformity and less susceptibility to sugar ends. The best results with ESN indicate an early sidedress application provides the best yield and quality. However, there is interest in using ESN as a preplant fertilizer. In previous studies, use of ESN shows the greatest advantage of reducing nitrate leaching when excessive rainfall occurs in May and June. Because the release characteristics of

ESN can affect tuber set and bulking of potatoes, evaluation of this new technology is essential for adoption. The use of newer cultivars in combination with newer cost effective urea coated fertilizer technology has the potential to greatly improve N use efficiency in potato and reduce nitrate losses. Research over different growing seasons is needed to evaluate the N response and use efficiency characteristics of new cultivars in comparison with Russet Burbank, as well as to estimate an N budget (inputs vs. outputs). These data will be useful for growers to more efficiently manage N for these cultivars.
The overall goal of this research is to optimize N fertilizer management for new processing potato cultivars under Minnesota growing conditions. Specific objectives include: a) Determine the effect of N rate and source on tuber yield and quality of new cultivars/selections potato cultivars, and b) Evaluate the effectiveness of a cost-effective coated urea product on tuber yield and quality of the potato cultivars/selections. This is the second year of the study.

Materials and Methods

This study was conducted at the Sand Plain Research Farm in Becker, Minnesota on a Hubbard loamy sand soil. The previous crop was rye. Selected soil chemical properties before planting were as follows (0-6"): pH, 4.9; organic matter, 2.2%; Bray P1, 19 ppm; ammonium acetate extractable K, Ca, and Mg, 62, 319, and 37 ppm, respectively; Ca-phosphate extractable SO_4-S, 3.3 ppm; and DTPA extractable Zn, Cu, Fe, and Mn, 1.2, 0.5, 99.1, and 31.6 ppm, respectively. Extractable nitrate-N and ammonium-N in the top 2 ft of soil were 10.9 and 14.1 lb/A, respectively.

Prior to planting, 250 lb/A 0-0-60 and 250 lb/A 0-0-22 were broadcast and incorporated with a moldboard plow. Four, 20-ft rows were planted for each plot with the middle two rows used for sampling and harvest. Whole "B" seed of Russet Burbank, and cut "A" seed of Umatilla, Premier, and Bannock were hand planted in furrows on April 24, 2009. Row spacing was 12 inches within each row and 36 inches between rows. Each treatment was replicated four times for each variety in a randomized complete block design. Admire Pro was applied in-furrow for beetle control, along with the systemic fungicides Quadris and Ultra Flourish. Weeds, diseases, and other insects were controlled using standard practices. Rainfall was supplemented with sprinkler irrigation using the checkbook method of irrigation scheduling.

Each cultivar was subjected to ten N treatments with different N sources, rates, and application timing as described in Table 1 below. A complete factorial arrangement was used with cultivar and N treatment as main effects.

Preplant ESN fertilizer was applied 8 days before planting on April 16 and disked in. The 30-lb N/A application at planting as MAP was banded 3 inches to each side and 2 inches below the seed piece using a belt type applicator. For all treatments, banded fertilizer at planting included 130 lb P_2O_5/A as monommonium phosphate or triple superphosphate (for the 0 N control), 180 lb K_2O/A as potassium chloride and potassium magnesium sulfate, and 20 lb Mg/A and 45 lb S/A as potassium magnesium sulfate. Emergence N applications were supplied as urea and mechanically incorporated during hilling. Also at emergence, 950 lb/A gypsum was applied and incorporated into the hill. Post-hilling N was applied by hand as 50% granular urea-N and 50% ammonium nitrate-N, which was watered-in with overhead irrigation to simulate fertigation with a 28% UAN solution. Emergence fertilizer was applied on May 15 and post-hilling N was applied on June 15, June 25, July 6, and July 16.

A WatchDog weather station from Spectrum Technologies was used to monitor rainfall, air temperature, and soil temperature at the fertilizer band depth. Measured amounts of ESN fertilizer were placed in plastic mesh bags and buried at the depth of fertilizer placement when both the preplant and emergence applications were made. Bags were removed on April 28, May 11, May 22, June 3, June 16, July 1, July 22, Aug 12, Sept 23, and Oct 20 to track N release over time. Plant stands and stem number per plant were measured on June 9. Petiole samples were collected from the 4th leaf from the terminal on three dates: June 24, July 7, and July 21. Petioles were analyzed for nitrate-N on a dry weight basis.

Table 1. Nitrogen treatments tested on processing potato varieties.

Treatment	Preplant	Planting	Emergence	Post-hilling**	Total
	------------------------ N sources* and rates (lb N/A) ------------------------				
1	0	0	0	0	0
2	0	30 MAP	50 Urea	10 UAN x 4	120
3	0	30 MAP	70 Urea	20 UAN x 4	180
4	0	30 MAP	90 Urea	30 UAN x 4	240
5	0	30 MAP	50 Urea	40 UAN x 4	240
6	0	30 MAP	90 Urea	45 UAN x 4	300
7	150 ESN	30 MAP	0	0	180
8	210 ESN	30 MAP	0	0	240
9	0	30 MAP	150 ESN	0	180
10	0	30 MAP	210 ESN	0	240

*ESN = Environmentally Smart Nitrogen (44-0-0), MAP = monoammonium phosphate, urea = 46-0-0, UAN = a combination of granular urea and ammonium nitrate.
**Post-hilling N was applied 4 times at 10-11 day intervals.

Vines were harvested on Sept 22 from two, 10-ft sections of row, followed by mechanically beating the vines over the entire plot area. Plots were machine harvested on Sept 30 and total tuber yield and graded yield were measured. Sub-samples of vines and tubers were collected to determine moisture percentage and N concentrations, which were then used to calculate N uptake and distribution within the plant (Note: all the data for N uptake were not available at the time of this report and therefore will be presented at a later time). Tuber sub-samples were also used to determine tuber specific gravity and the incidence of hollow heart and brown center. Stem and bud end sugar contents after frying were determined after harvest. Additional fry tests will be made after six months of storage at about 45 F.

RESULTS

Weather

Rainfall and irrigation for the 2009 growing season are provided in Figure 1. From April 21 to September 22, approximately 13.4 inches of rainfall was supplemented with 16.2 inches of irrigation. There were no leaching events early in the season. Leaching events (greater than 1 inch of water) occurred at 53, 106, and 117 days after planting. Air temperature measurements and soil temperature and moisture measurements in the hill (4-5 inches below the top of the hill) are provided in Figure 2.

Nitrogen Release from ESN

Figure 3 shows release of N from ESN applied preplant and at emergence. Release of N from ESN tended to be faster than that recorded in previous years. In 2007, approximately 90% of N was released by 70 days after planting for preplanted fertilizer and by 80 days after planting for ESN applied at emergence. In 2008, 80% had been released by 40 days after planting for the preplant application and by about 50 days for the emergence application. In 2009, 80% had been released by 40 days after planting for the preplant application and by about 55 days for the emergence application. Differences in release rate are likely due to difference in abrasion of the coating as well as temperature difference. Temperatures in 2009 were cooler than those in 2008.

Tuber Yield, Stand Count, Stem Number, and Vine Dry Matter

Nitrogen rate, source, and timing comparisons on yield

Tables 2-5 show the effects of N application rate, source, and timing on tuber yield and size distribution as well as stand count, stem number and vine dry matter at harvest for the four processing varieties. For Russet Burbank (Table 2), marketable and total yields increased with increasing N rate with optimum yield between 240 and 300 lb N/A depending on timing and source. As in 2008, numerically highest total, marketable and #1 yields were with ESN applied preplant at the 240 lb N/A rate. Yields with preplant ESN tended to be higher than those with emergence applied ESN, although these differences were not significant. Within conventional N sources at the 240 lb N/A rate, N applied earlier (treatment 4) resulted in yields that were statistically the same as N applied later in the season (treatment 5). At equivalent N rates, N source did not significantly affect yield. For Umatilla (Table 3), marketable and total yields increased with increasing N rate with optimum yield between 240 to 300 lb N/A depending on timing and source. Numerically highest yields were with conventional N 300 lb N/A rate, while numerically highest total yields were with ESN applied preplant at the 240 lb N/A rate. Yields with preplant ESN tended to be higher than those with emergence applied ESN. At the 240 lb N/A rate, yields with emergence applied ESN tended to be lower than prelant applied ESN and conventional N applied at 300 lb N/A. Within conventional N sources at the 240 lb N/A rate, N applied earlier (treatment 4) resulted in yields that were statistically the same as N applied later in the season (treatment 5). At equivalent N rates, N source did not significantly affect yield. For Premier, (Table 4), marketable and total yields increased with increasing N rate with optimum yield between 180 and 240 lb N/A depending on timing and source. Numerically highest total, marketable and #1 yields were with ESN applied preplant at the 240 lb N/A rate. Yields with preplant ESN were significantly higher than those with emergence applied ESN at the 180 lb N/A rate, but no significant differences due to timing were observed at the 240 lb N/A rate with ESN. Within conventional N sources at the 240 lb N/A rate, N applied earlier (treatment 4) resulted in yields that were statistically the same as N applied later in the season (treatment 5). At equivalent N rates, N source did not significantly affect marketable yield. For Bannock, (Table 5), marketable and total yields increased with increasing N rate with optimum yield between 180 to 240 lb N/A depending on timing and source. Numerically highest total, marketable and #1 yields were with ESN applied preplant at the 240 lb N/A rate. Yields with preplant ESN tended to be higher than those with emergence applied ESN, although statistically there were not differences among the ESN rates or timing tested. Within conventional N sources at the 240 lb N/A rate, N applied later (treatment 4) tended to result in numerically higher yields than N applied earlier in the season (treatment 5), although differences were not statistically significant. At the equivalent N rates, N source/timing did not significantly affect yield; although ESN treatments resulted in smaller tuber size that conventional N treatments. Tubers greater than 10 ounces increased with increasing N rate regardless of source/timing for all varieties.

General varietal comparisons for yield

Russet Burbank tended to be the highest yielding variety followed by Bannock and Premier, and then Umatilla. Premier, Bannock, and Umatilla all had fewer misshaped potatoes than Russet Burbank with Premier having the fewest #2 potatoes. Tubers greater than 6 and 10 oz were highest for Premier followed by Bannock, Russet Burbank and then Umatilla.

Nitrogen rate, source, and timing comparisons for stand count, stem number and vine dry matter at harvest

Stand count was generally not affected by N treatment, although for Premier, there was a slight reduction of 3% in stand in the control and 300 lb N/A rate compared with the other N treatments. Reasons for this reduction are not clear and probably not significant from a practical standpoint. In general, averaged over N treatments, stand was significantly lower for Bannock (~90%) compared with the other three varieties (> 98%). Stems per plant were not significantly affected by N treatments. The highest stem number per plant was with Bannock (4.8) followed by Umatilla (3.5) and then Premier (3.0) and Russet Burbank (2.9). This result is surprising since “B” seed, which usually results in higher stem number, was used for Russet Burbank, while cut “A” seed was used for the other varieties. Vine dry matter at harvest increased with increasing N rate for all varieties regardless of source. For Umatilla, late season N at the 240 lb N/A rate resulted in lower vine yield than early season applied at the same rate. Overall, vines died back earlier for Umatilla than the other varieties resulting in lowest vine yields. It is not know why Umatilla vines died back early, but it was probably due to disease. Early vine dieback in Umatilla resulted in poor utilization of late season applied N.

Tuber Quality

Nitrogen rate, source, and timing comparisons for tuber quality

Tables 6 to 9 show the effects of N application rate, source, and timing on tuber hollow heart, specific gravity and frying quality for the four processing varieties. Surface scab incidence was not affected by N treatment for any of the varieties. For Russet Burbank (Table 6), incidence of hollow heart ranged from 1 to 12% with inconsistent effects due to N treatment. The 180 lb N/A rate with conventional N resulted in the highest incidence while ESN applied at emergence at 240 lb N/A and the conventional N applied at 300 lb N/A had the lowest incidence. Timing of conventional N at the 240 lb N/A rate did not affect hollow hear in this year. Specific gravity was not affected by treatment and generally in the optimum for all treatments. Stem end chip color was not consistently affected by N treatments, but tended to be lighter with early applied N. It was darker for the control, ESN preplant 180 lb/A and late N 240 lb N/A rate treatments, while lightest for the conventional N at 180, early N at 240 lb N/A and ESN preplant at 240 lb N/A. Stem end AGT score was lowest in the control and highest with conventional N applied at 180 and 300 lb N/A. Stem end sucrose was not affected by treatment. Stem end glucose was highest in the control and lowest with preplant applied ESN at the 240 lb N/A rate. In general, stem end glucose decreased with increasing N rate and late season N tended increase stem end glucose. Bud end chip color, AGT score, sucrose and glucose were not affected affected by N treatment. For Umatilla (Table 7), incidence of hollow heart was quite low ranging from 0 to 4% with no effect due to N treatment. Specific gravity decreased with increasing conventional N rate and was lowest with late season N and N applied at the 300 lb N/A rate. ESN at the 240 lb N/A rate applied at emergence resulted in the highest specific gravity reading. Stem end chip color, AGT score, and glucose levels were not affected by N treatment. Stem end sucrose decreased with increasing N rate and was lower with preplant applied ESN than planting applied ESN. Bud end chip color, AGT score sucrose and glucose were not affected by treatment. For Premier (Table 8), incidence of hollow heart ranged from 3 to 16% and was not significantly affected by treatment. Specific gravity tended to decrease with increasing conventional N rate and was lowest with late season N and N applied at the 300 lb N/A rate. At equivalent N rates, ESN resulted in higher specific gravity than conventional N. Frying quality was also not affected by treatment. For Bannock (Table 9), incidence of hollow heart ranged from 6 to 15% and was not affected by treatment. Specific gravity ranged from 1.075 to 1.082 and was not affected by N treatment. Frying quality was also not affected by N treatment.

General varietal comparisons for tuber quality

Averaged over N treatments, hollow heart incidence was highest in Bannock, followed by Premier, Russet Burbank, and then Umatilla. Surface scab incidence was highest with Umatilla, followed by Russet Burbank and then Bannock and Premier. Specific gravity was highest in Russet Burbank and Umatilla and followed by Premier and then Bannock. Stem and bud chip color was darkest for Russet Burbank and lowest for Premier. AGT scores were highest for Premier and lowest for Russet Burbank. Stem end glucose concentrations were highest for Russet Burbank followed by Bannock, and then Premier, and Umatilla. Stem end sucrose was highest with Umatilla and Premier followed by Bannock and then Russet Burbank. Bud end glucose concentrations were highest for Bannock and Russet Burbank, followed by Umatilla and then Premier. Bud end sucrose was highest with Premier and Russet Burbank followed by Umatilla and Bannock.

Petiole Nitrate-N Concentrations

Nitrogen rate, source, and timing comparisons

Petiole NO_3-N concentrations on three dates as affected by N rate, N source, and N timing are presented in Tables 10-13. As expected, petiole NO_3-N generally increased with increasing N rate for all varieties and decreased as the season progressed. Petiole NO_3-N levels with the 300 lb N/A rate applied through the season were generally the highest of any treatment, especially later in the season. Late season applied conventional Nat the 240 lb N/A rate had inconsistent effects on petiole NO_3-N. For Russet Burbank and Premier, petiole NO_3-N was lower at all sampling dates with late applied N compared with early applied N. For Umatilla and Bannock, this trend was the same for the first two sampling dates, but by the third sampling date petiole NO_3-N with late season N was higher than with early season N, which is what would be expected. Reasons for the lower petiole NO_3-N concentrations for Russet Burbank and Premier with late season N are not known.

At equivalent N rates, differences between urea and ESN treatments depended on the time of the season. For the first sampling date (June 24), petiole NO_3-N concentrations were similar between the two N sources for preplant applied ESN and early applied conventional N. Concentrations were higher with early applied N than when ESN was applied at planting and when late season N was applied. The similarity between ESN and split applied conventional N is consistent with the release of N from the polymer, which appears to be faster than in earlier studies. By the second sampling date (July 7), planting ESN treatments tended to result in petiole NO_3-N levels higher than conventional N especially at the 240 lb N/A rate. Preplant applied ESN resulted in petiole NO_3-N levels that were either the same or slightly lower than conventional. By the last sampling date (July 21), petiole NO_3-N levels were lower with ESN compared with conventional N when applied at equivalent N rates. These lower petiole NO_3-N levels with ESN later in the season are again consistent with the faster release form the polymer than in previous years.

General varietal comparisons for petiole NO_3-N

At the June 24 sampling date, petiole nitrate levels were higher for Umatilla and Premier and Bannock than for Russet Burbank. Difference became less distinct towards the July 7 sampling date. However, Umatilla petiole NO_3-N levels were higher than those for the other cultivars. Based on yield responses to N, petiole nitrate levels should be higher for Umatilla during the growing season than other varieties tested.

CONCLUSIONS

As in 2008, release of N from ESN was 20-30 days faster in 2009 than that recorded in previous years, suggesting that the there was more abrasion of the coated with the ESN source used the past two years. In general, marketable and total yields of all varieties increased with increasing N rate with all varieties responding to conventional N up to the 300 lb N/A rate, with optimum yield between 240 to 300 lb N/A depending on timing and source. For conventional N at the 240 lb N/A rate more up front N resulted in higher yields than lat applied N for all varieties. This is in contrast to 2008 when Umatilla responded better to late season-applied N. The difference in 2009 was that Umatilla vines died back early due to disease and were not able to fully utilize the late applied N. At equivalent N rates, yields with ESN applied preplant were generally higher than those when ESN was applied at emergence when conventional N was split applied.

Russet Burbank tended to be the highest yielding variety followed by Bannock and Premier, and then Umatilla. Premier, Bannock, and Umatilla all had fewer misshaped potatoes than Russet Burbank with Premier having the fewest #2 potatoes. Tubers greater than 6 and 10 oz were highest for Premier followed by Bannock, Russet Burbank and then Umatilla. Surprisingly, hollow heart incidence was highest in Bannock, followed by Premier, Russet Burbank, and then Umatilla. Surface scab incidence was highest with Umatilla, followed by Russet Burbank and then Bannock and Premier. Specific gravity was highest in Russet Burbank and Umatilla and followed by Premier and then Bannock. Stem and Bud chip color was darkest for Russet Burbank and lowest for Premier.

Support for this project was provided in 2005 by the Environment and Natural Resources Trust Fund as recommended by the Legislative Commission on Minnesota Resources, Agrium Inc., and the Area II Potato Growers Association.

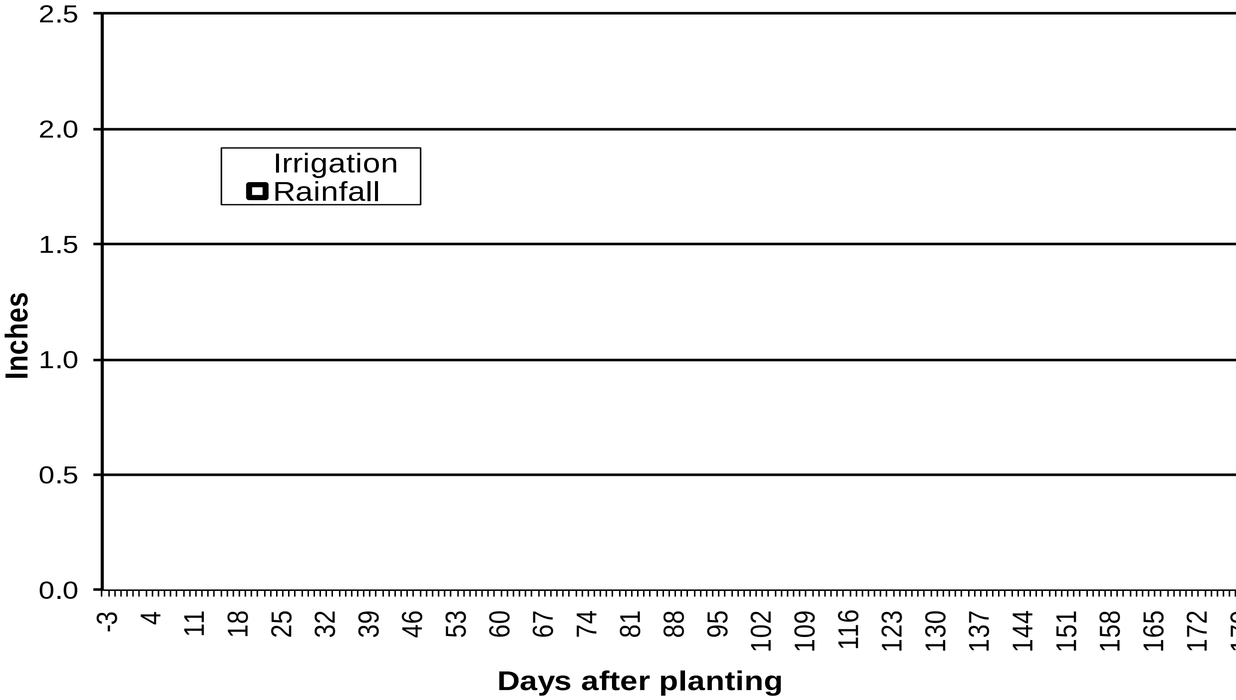

Figure 1. Rainfall and irrigation over the 2009 growing season.

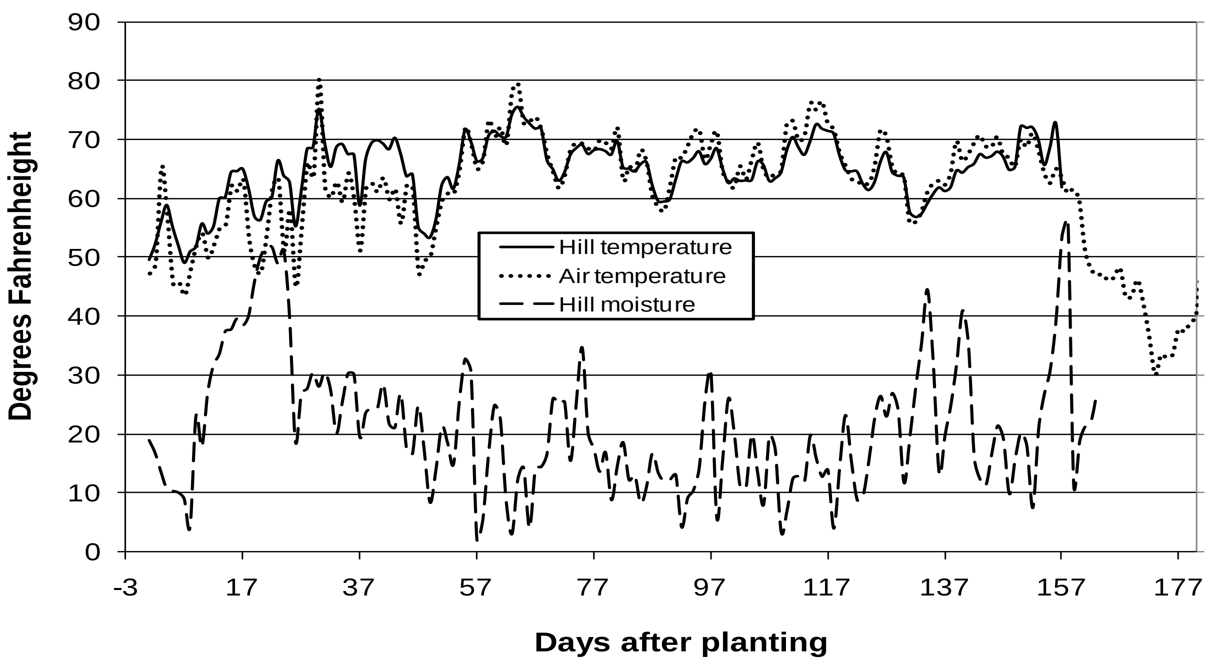

Figure 2. Average daily air temperature and soil moisture and temperature at the 4-5 inch inch depth below the top of the hill over the growing season.

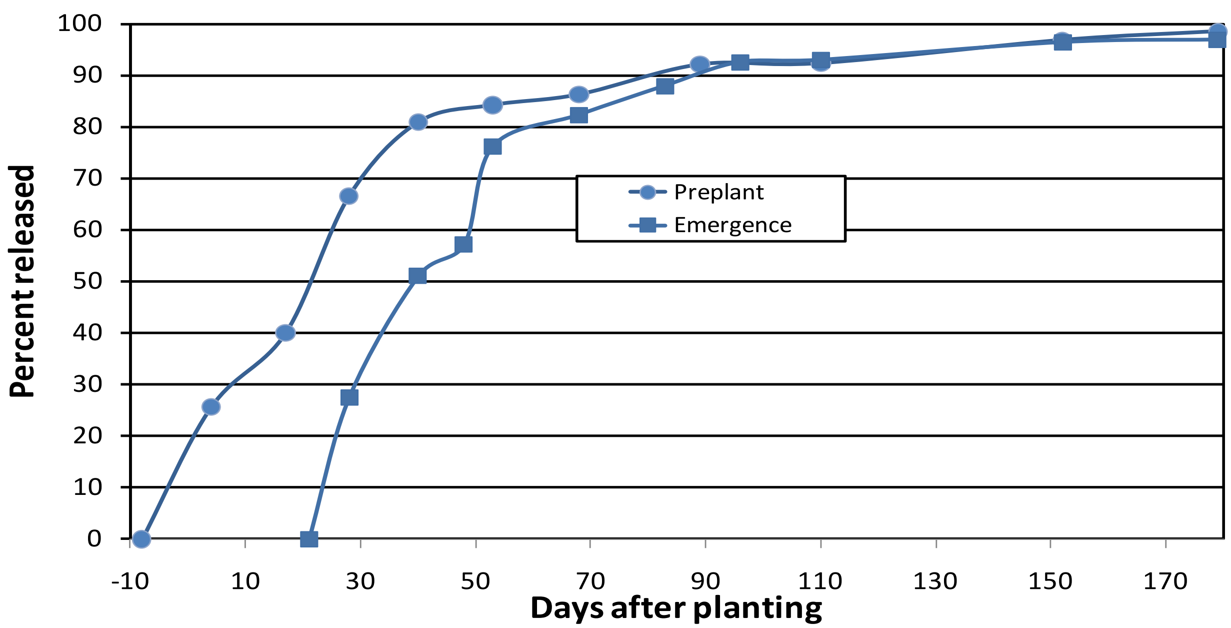

Figure 3. N released from ESN applied preplant and at emergence in 2009.

Table 2. Effect of N rate, source, and timing on Russet Burbank tuber yield and size distribution, stand count, stem number and vine dry matter at harvest.

Nitrogen Treatments				Tuber Yield													
Trtmt	N Source	N Rate	N Timing[1]	0-3 oz	3-6 oz	6-10 oz	10-14 oz	> 14 oz	Total	#1 > 3 oz	# 2 > 3 oz	Total marketable	> 6 oz	> 10 oz	Stand	Stems	Vine DM
#		lb N / A	PP, P, E, PH	---------------------------- cwt / A							----------------------------		---------- %	-------------	%	per Plant	Tons/Acre
1	control	30	0, 30, 0, 0	69.6	264.2	165.1	35.0	15.7	549.6	270.4	209.6	480.0	39.2	9.0	99.3	3.2	0.47
2	urea	120	0, 30, 50, 40	69.4	234.3	173.9	68.5	46.7	592.8	321.4	202.0	523.4	48.8	19.5	99.3	2.7	0.62
3	urea	180	0, 30, 70, 80	72.9	210.4	188.7	71.6	84.0	627.7	364.9	189.9	554.8	54.9	24.9	100.0	2.8	0.97
4	urea	240	0, 30, 90, 120	59.4	167.6	202.8	105.5	144.9	680.2	413.6	207.2	620.8	66.3	36.4	99.3	3.1	1.01
5	urea	240	0, 30, 50, 160	64.9	188.2	195.3	105.6	125.9	679.9	413.8	201.2	615.0	62.5	33.6	99.3	3.0	1.01
6	urea	300	0, 30, 90, 180	47.8	159.3	196.5	116.1	167.8	687.5	439.9	199.8	639.7	69.9	41.4	98.5	2.6	1.12
7	ESN	180	150, 30, 0, 0	63.7	194.7	209.0	110.8	82.4	660.7	439.7	157.3	597.0	61.0	29.4	100.0	3.0	0.88
8	ESN	240	210, 30, 0, 0	54.2	170.1	206.7	120.3	149.6	700.9	461.5	185.2	646.7	68.0	38.5	99.3	2.8	1.24
9	ESN	180	0, 30, 150, 0	59.4	209.9	231.2	87.8	80.3	668.6	400.9	208.3	609.2	59.6	25.1	100.0	3.0	0.63
10	ESN	240	0, 30, 210, 0	61.7	210.2	231.1	104.1	86.3	693.4	414.7	217.0	631.7	60.7	27.3	100.0	2.9	0.94
Significance[2]				*	**	**	**	**	**	**	NS	**	**	**	NS	NS	**
LSD (0.10)				14.3	44.6	33.0	22.5	50.0	39.9	41.9	--	39.8	6.3	8.4	--	--	0.29

[1]PP, P, E, PH = Preplant, Planting, Emergence, and Post-Hilling, respectively; 4 post-hilling applications were as follows: 20%, 20%, 30%, 30%.

[2]NS = Non-significant; ++, *, ** = Significant at 10%, 5%, and 1%, respectively.

Table 3. . Effect of N rate, source, and timing on Umatilla Russet tuber yield and size distribution, stand count, stem number and vine dry matter at harvest.

Nitrogen Treatments				Tuber Yield													
Trtmt	N Source	N Rate	N Timing[1]	0-3 oz	3-6 oz	6-10 oz	10-14 oz	> 14 oz	Total	#1 > 3 oz	# 2 > 3 oz	Total marketable	> 6 oz	> 10 oz	Stand	Stems	Vine DM
#		lb N / A	PP, P, E, PH	---------------------------- cwt / A							----------------------------		---------- %	-------------	%	per Plant	Tons/Acre
1	control	30	0, 30, 0, 0	72.9	212.3	114.0	8.3	0.0	407.4	329.6	5.0	334.6	30.0	2.0	99.3	3.6	0.25
2	Urea	120	0, 30, 50, 40	72.7	218.2	201.1	17.2	6.5	515.7	434.5	8.5	443.0	42.9	4.4	98.5	3.5	0.30
3	Urea	180	0, 30, 70, 80	70.7	238.3	226.0	48.5	14.5	598.0	497.7	29.5	527.3	48.3	10.6	98.0	3.6	0.45
4	Urea	240	0, 30, 90, 120	62.0	197.8	244.6	68.5	31.4	604.3	498.6	43.7	542.3	56.9	16.5	97.0	3.6	0.62
5	Urea	240	0, 30, 50, 160	66.2	211.3	223.3	57.3	25.9	584.1	470.4	47.5	517.9	52.3	14.1	96.5	3.3	0.44
6	Urea	300	0, 30, 90, 180	58.5	211.2	225.3	68.8	58.0	621.8	494.9	68.4	563.3	56.5	20.4	97.3	3.3	0.49
7	ESN	180	150, 30, 0, 0	65.7	202.5	240.8	72.6	37.4	619.0	510.1	43.2	553.3	56.4	17.7	98.5	3.9	0.49
8	ESN	240	210, 30, 0, 0	56.9	217.7	230.7	72.3	47.5	625.0	520.3	47.8	568.1	56.0	19.1	100.0	3.5	0.52
9	ESN	180	0, 30, 150, 0	65.8	217.1	227.8	40.3	19.4	570.5	486.0	18.7	504.7	50.4	10.4	97.8	3.8	0.41
10	ESN	240	0, 30, 210, 0	55.2	195.4	238.9	67.7	26.9	584.0	470.9	57.9	528.9	57.1	16.2	98.5	3.5	0.49
Significance[2]				NS	NS	**	**	**	**	**	**	**	**	**	NS	NS	**
LSD (0.10)				--	--	33.5	15.3	16.1	41.5	39.8	18.0	42.4	5.8	3.7	--	--	0.16

[1]PP, P, E, PH = Preplant, Planting, Emergence, and Post-Hilling, respectively; 4 post-hilling applications were as follows: 20%, 20%, 30%, 30%.

[2]NS = Non-significant; ++, *, ** = Significant at 10%, 5%, and 1%, respectively.

Table 4. Effect of N rate, source, and timing on Premier Russet tuber yield and size distribution, stand count, stem number and vine dry matter at harvest.

Nitrogen Treatments				Tuber Yield													
Trtmt #	N Source	N Rate lb N / A	N Timing[1] PP, P, E, PH	0-3 oz	3-6 oz	6-10 oz	10-14 oz	> 14 oz	Total	#1 > 3 oz	# 2 > 3 oz	Total marketable	> 6 oz	> 10 oz	Stand %	Stems per Plant	Vine DM Tons/Acre
				cwt / A									%				
1	control	30	0, 30, 0, 0	22.0	94.6	197.6	103.7	49.9	467.8	442.4	3.5	445.8	74.9	32.7	97.0	2.9	0.47
2	Urea	120	0, 30, 50, 40	17.9	77.6	175.2	133.5	126.8	530.9	501.8	11.3	513.1	81.9	48.7	100.0	2.7	0.54
3	Urea	180	0, 30, 70, 80	18.6	66.7	159.9	113.3	196.5	554.9	529.0	7.4	536.4	84.6	55.8	100.0	3.1	0.87
4	Urea	240	0, 30, 90, 120	18.7	66.4	140.0	114.4	219.1	558.6	528.8	11.1	539.9	84.8	59.7	100.0	3.1	0.95
5	Urea	240	0, 30, 50, 160	15.1	73.4	158.6	124.7	189.9	561.5	514.4	32.1	546.5	84.2	56.1	99.3	2.8	0.90
6	Urea	300	0, 30, 90, 180	18.4	52.6	136.3	116.6	241.2	565.2	525.7	21.1	546.8	87.4	63.3	97.8	2.6	1.02
7	ESN	180	150, 30, 0, 0	22.7	79.8	164.1	127.5	174.3	568.3	528.7	17.0	545.7	81.9	53.0	100.0	3.2	0.77
8	ESN	240	210, 30, 0, 0	19.0	63.8	165.5	123.3	216.7	588.3	537.5	31.8	569.3	85.9	57.4	99.3	3.1	1.20
9	ESN	180	0, 30, 150, 0	19.5	70.9	175.6	122.6	139.7	528.3	497.9	10.9	508.8	82.9	49.7	100.0	3.3	0.86
10	ESN	240	0, 30, 210, 0	17.4	57.9	153.8	142.2	198.0	569.3	524.3	27.6	551.9	86.8	59.9	100.0	3.1	0.98
			Significance[2]	NS	**	NS	NS	**	**	**	**	**	**	**	*	NS	**
			LSD (0.10)	--	14.1	--	--	51.5	27.3	27.5	8.6	28.1	3.3	8.3	2.0	--	0.23

[1]PP, P, E, PH = Preplant, Planting, Emergence, and Post-Hilling, respectively; 4 post-hilling applications were as follows: 20%, 20%, 30%, 30%.

[2]NS = Non-significant; ++, *, ** = Significant at 10%, 5%, and 1%, respectively.

Table 5. Effect of N rate, source, and timing on Bannock Russet tuber yield and size distribution, stand count, stem number and vine dry matter at harvest.

Nitrogen Treatments				Tuber Yield													
Trtmt #	N Source	N Rate lb N / A	N Timing[1] PP, P, E, PH	0-3 oz	3-6 oz	6-10 oz	10-14 oz	> 14 oz	Total	#1 > 3 oz	# 2 > 3 oz	Total marketable	> 6 oz	> 10 oz	Stand %	Stems per Plant	Vine DM Tons/Acre
				cwt / A									%				
1	control	30	0, 30, 0, 0	42.8	154.6	188.4	62.9	18.7	467.3	413.2	11.3	424.5	57.6	17.4	87.0	4.8	0.46
2	urea	120	0, 30, 50, 40	30.9	131.7	206.8	118.7	59.7	547.9	498.2	18.8	517.0	70.4	32.7	90.3	4.8	0.68
3	urea	180	0, 30, 70, 80	33.5	115.0	202.5	139.2	95.9	585.9	524.4	28.1	552.5	74.9	40.3	89.0	5.1	1.19
4	urea	240	0, 30, 90, 120	29.4	94.5	200.8	136.9	119.8	581.4	517.1	34.9	552.0	79.1	45.2	90.3	4.9	1.40
5	urea	240	0, 30, 50, 160	27.0	99.6	198.2	143.6	130.0	598.4	517.5	53.9	571.4	78.8	45.9	91.5	4.7	1.57
6	urea	300	0, 30, 90, 180	28.3	95.0	189.0	130.1	156.7	599.1	530.6	40.2	570.8	79.6	47.9	89.0	4.6	1.65
7	ESN	180	150, 30, 0, 0	38.7	147.4	224.6	113.0	77.1	600.7	540.1	21.9	562.0	69.3	31.9	90.3	5.0	1.06
8	ESN	240	210, 30, 0, 0	27.7	124.9	191.1	128.9	135.4	608.0	548.3	32.1	580.3	75.0	43.3	93.8	4.3	1.42
9	ESN	180	0, 30, 150, 0	33.4	127.5	239.3	120.0	83.2	603.5	540.3	29.8	570.1	73.3	33.6	93.5	4.8	1.14
10	ESN	240	0, 30, 210, 0	31.8	128.5	189.3	116.2	135.3	601.1	542.0	27.3	569.3	73.3	41.8	88.3	4.6	1.41
			Significance[2]	NS	*	NS	**	**	*	*	**	**	**	**	NS	NS	**
			LSD (0.10)	--	34.0	--	21.8	28.9	74.7	64.4	18.2	64.5	5.3	6.1	--	--	0.38

[1]PP, P, E, PH = Preplant, Planting, Emergence, and Post-Hilling, respectively; 4 post-hilling applications were as follows: 20%, 20%, 30%, 30%.

[2]NS = Non-significant; ++, *, ** = Significant at 10%, 5%, and 1%, respectively.

Table 6. Effect of N rate, source, and timing on Russet Burbank tuber quality, frying quality, and sucrose and glucose levels.

Nitrogen Treatments				Tuber Quality			Frying Quality							
Trtmt	N Source	N Rate	N Timing[1]	Hollow Heart	Scab	Specific Gravity	STEM				BUD			
#		lb N / A	PP, P, E, PH	%	%		Chip Color	AGT Score	Sucrose	Glucose	Chip Color	AGT Score	Sucrose	Glucose
1	control	30	0, 30, 0, 0	4.0	14.0	1.0827	3.0	48.8	1.122	4.499	2.5	55.0	1.704	0.465
2	urea	120	0, 30, 50, 40	9.0	12.0	1.0854	2.5	53.8	0.405	3.590	2.5	56.0	1.825	0.536
3	urea	180	0, 30, 70, 80	12.0	14.3	1.0849	2.0	56.0	0.395	3.142	2.8	53.8	1.650	0.294
4	urea	240	0, 30, 90, 120	2.0	14.0	1.0851	2.3	55.3	0.602	2.131	2.8	53.5	1.301	0.285
5	urea	240	0, 30, 50, 160	4.0	16.0	1.0852	3.0	53.8	0.437	3.043	2.8	53.5	1.604	0.352
6	urea	300	0, 30, 90, 180	1.0	18.5	1.0848	2.3	56.5	0.795	2.385	2.5	55.0	1.587	0.540
7	ESN	180	150, 30, 0, 0	8.0	16.0	1.0860	3.0	52.5	0.441	2.930	3	52.0	1.687	0.407
8	ESN	240	210, 30, 0, 0	8.0	18.3	1.0879	2.3	54.8	0.692	1.520	2.5	55.3	1.772	0.477
9	ESN	180	0, 30, 150, 0	3.0	7.0	1.0874	2.8	52.5	0.570	3.255	2.8	52.3	1.716	0.724
10	ESN	240	0, 30, 210, 0	1.0	14.0	1.0844	2.8	54.3	0.829	2.501	2.5	55.5	1.971	0.442
Significance[2]				*	NS	NS	**	**	NS	++	NS	NS	NS	NS
LSD (0.10)				6.6	- -	- -	0.5	3.4	--	1.857	--	--	--	--

[1]PP, P, E, PH = Preplant, Planting, Emergence, and Post-Hilling, respectively; 4 post-hilling applications were as follows: 20%, 20%, 30%, 30%.

[2]NS = Non-significant; ++, *, ** = Significant at 10%, 5%, and 1%, respectively.

Table 7. Effect of N rate, source, and timing on Umatilla Russet tuber quality, frying quality, and sucrose and glucose levels.

Nitrogen Treatments				Tuber Quality			Frying Quality							
Trtmt	N Source	N Rate	N Timing[1]	Hollow Heart	Scab	Specific Gravity	STEM				BUD			
#		lb N / A	PP, P, E, PH	%	%		Chip Color	AGT Score	Sucrose	Glucose	Chip Color	AGT Score	Sucrose	Glucose
1	control	30	0, 30, 0, 0	0.0	11.0	1.0867	2.0	56.5	1.145	0.933	2.5	54.0	1.489	0.442
2	urea	120	0, 30, 50, 40	3.0	15.0	1.0868	2.3	54.5	1.251	0.691	2.5	54.3	1.516	0.393
3	urea	180	0, 30, 70, 80	3.0	17.0	1.0841	2.0	58.0	1.066	0.890	2.3	56.5	1.731	0.288
4	urea	240	0, 30, 90, 120	3.0	30.0	1.0836	2.0	56.0	1.080	0.811	2.0	57.0	1.922	0.575
5	urea	240	0, 30, 50, 160	3.0	13.0	1.0814	2.3	55.3	1.055	1.026	2.5	53.8	1.340	0.376
6	urea	300	0, 30, 90, 180	4.0	22.0	1.0768	2.0	57.5	1.111	0.955	2.0	57.5	1.681	0.281
7	ESN	180	150, 30, 0, 0	1.0	22.3	1.0835	2.3	56.0	0.993	0.845	2.5	53.8	1.460	0.363
8	ESN	240	210, 30, 0, 0	0.0	24.0	1.0838	2.3	56.5	0.985	0.899	2.5	54.8	1.703	0.380
9	ESN	180	0, 30, 150, 0	2.0	16.3	1.0885	2.0	58.3	1.717	1.276	2.3	55.3	1.736	0.405
10	ESN	240	0, 30, 210, 0	3.0	22.0	1.0911	2.0	57.5	1.471	1.026	2.3	56.3	1.642	0.433
Significance[2]				NS	NS	*	NS	NS	*	NS	NS	NS	NS	NS
LSD (0.10)				--	--	0.0078	--	--	0.3987	--	--	--	--	--

[1]PP, P, E, PH = Preplant, Planting, Emergence, and Post-Hilling, respectively; 4 post-hilling applications were as follows: 20%, 20%, 30%, 30%.

[2]NS = Non-significant; ++, *, ** = Significant at 10%, 5%, and 1%, respectively.

Table 8. Effect of N rate, source, and timing on Premier Russet tuber quality, frying quality, and sucrose and glucose levels.

Nitrogen Treatments				Tuber Quality			Frying Quality							
	N	N	N	Hollow		Specific	STEM				BUD			
Trtmt #	Source	Rate lb N / A	Timing[1] PP, P, E, PH	Heart %	Scab %	Gravity	Chip Color	AGT Score	Sucrose	Glucose	Chip Color	AGT Score	Sucrose	Glucose
1	control	30	0, 30, 0, 0	10.0	11.0	1.0829	1.8	60.8	1.239	1.085	2.0	59.8	1.861	0.271
2	urea	120	0, 30, 50, 40	13.0	11.3	1.0852	2.3	59.3	0.886	1.259	2.0	61.3	1.705	0.327
3	urea	180	0, 30, 70, 80	10.3	10.3	1.0838	2.0	60.3	1.045	0.788	2.0	60.3	1.683	0.302
4	urea	240	0, 30, 90, 120	3.0	13.0	1.0817	2.0	58.3	1.140	0.770	2.0	61.8	1.520	0.326
5	urea	240	0, 30, 50, 160	7.0	13.0	1.0793	2.0	59.3	1.029	0.835	2.0	59.3	1.935	0.138
6	urea	300	0, 30, 90, 180	8.0	11.0	1.0800	2.0	60.5	1.160	0.842	2.0	60.8	1.785	0.150
7	ESN	180	150, 30, 0, 0	16.0	10.0	1.0859	2.0	58.0	1.235	1.011	2.3	58.5	1.816	0.409
8	ESN	240	210, 30, 0, 0	4.3	7.8	1.0863	2.0	61.3	1.125	0.538	2.0	60.0	1.965	0.195
9	ESN	180	0, 30, 150, 0	4.0	10.0	1.0896	2.0	61.0	1.334	0.914	2.0	59.5	1.864	0.099
10	ESN	240	0, 30, 210, 0	8.0	8.0	1.0848	1.8	60.3	1.014	0.577	2.0	58.5	1.957	0.186
Significance[2]				NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS
LSD (0.10)				--	--	0.0052	--	--	--	--	--	--	--	--

[1]PP, P, E, PH = Preplant, Planting, Emergence, and Post-Hilling, respectively; 4 post-hilling applications were as follows: 20%, 20%, 30%, 30%.

[2]NS = Non-significant; ++, *, ** = Significant at 10%, 5%, and 1%, respectively.

Table 9. Effect of N rate, source, and timing on Bannock Russet tuber quality, frying quality, and sucrose and glucose levels.

Nitrogen Treatments				Tuber Quality			Frying Quality							
	N	N	N	Hollow		Specific	STEM				BUD			
Trtmt #	Source	Rate lb N / A	Timing[1] PP, P, E, PH	Heart %	Scab %	Gravity	Chip Color	AGT Score	Sucrose	Glucose	Chip Color	AGT Score	Sucrose	Glucose
1	control	30	0, 30, 0, 0	15.0	12.0	1.0778	2.8	54.0	0.806	2.171	2.0	56.0	1.226	0.851
2	urea	120	0, 30, 50, 40	9.0	7.0	1.0816	2.8	53.0	0.597	1.911	2.5	55.8	1.437	0.449
3	urea	180	0, 30, 70, 80	8.0	13.0	1.0808	2.8	53.3	0.676	2.503	2.0	57.3	1.388	0.475
4	urea	240	0, 30, 90, 120	9.0	12.0	1.0802	2.3	55.0	1.017	2.174	2.3	55.5	1.700	0.613
5	urea	240	0, 30, 50, 160	11.0	11.0	1.0801	2.3	55.3	0.840	1.690	2.5	55.0	1.538	0.285
6	urea	300	0, 30, 90, 180	6.0	3.0	1.0788	2.3	55.0	0.756	1.928	2.5	57.0	1.713	0.504
7	ESN	180	150, 30, 0, 0	15.0	18.0	1.0819	2.5	53.8	0.959	2.024	2.5	55.3	1.477	0.807
8	ESN	240	210, 30, 0, 0	14.3	9.3	1.0752	2.3	56.0	0.826	1.906	2.3	55.3	1.553	0.483
9	ESN	180	0, 30, 150, 0	6.0	10.0	1.0822	2.8	53.8	0.870	1.430	2.0	57.5	1.248	0.502
10	ESN	240	0, 30, 210, 0	10.0	14.0	1.0775	2.8	53.5	0.790	1.502	2.3	56.0	1.504	0.306
Significance[2]				NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
LSD (0.10)				--	--	--	--	--	--	--	--	--	--	--

[1]PP, P, E, PH = Preplant, Planting, Emergence, and Post-Hilling, respectively; 4 post-hilling applications were as follows: 20%, 20%, 30%, 30%.

[2]NS = Non-significant; ++, *, ** = Significant at 10%, 5%, and 1%, respectively.

Table 10. Effect of N rate, source, and timing on Russet Burbank petiole nitrate-N levels.

Nitrogen Treatments				NO_3-N, ppm		
	N	N	N			
Trtmt	Source	Rate	Timing[1]			
#		lb N / A	PP, P, E, PH	June 24	July 7	July 21
1	control	30	0, 30, 0, 0	6939	512	192
2	urea	120	0, 30, 50, 40	13433	5710	2224
3	urea	180	0, 30, 70, 80	16598	9488	8740
4	urea	240	0, 30, 90, 120	18429	13467	13690
5	urea	240	0, 30, 50, 160	16130	10511	11498
6	urea	300	0, 30, 90, 180	17618	14558	14035
7	ESN	180	150, 30, 0, 0	16147	10866	4865
8	ESN	240	210, 30, 0, 0	17319	13425	8819
9	ESN	180	0, 30, 150, 0	16028	11623	6003
10	ESN	240	0, 30, 210, 0	15755	13488	9844
			Significance[2]	**	**	**
			LSD (0.10)	1468	1676	1863

[1]PP, P, E, PH = Preplant, Planting, Emergence, and Post-Hilling, respectively;
4 post-hilling applications were as follows: 20%, 20%, 30%, 30%.
[2]NS = Non-significant; ++, *, ** = Significant at 10%, 5%, and 1%, respectively.

Table 11. Effect of N rate, source, and timing on Umatilla Russet petiole nitrate-N levels.

Nitrogen Treatments				NO_3-N, ppm		
	N	N	N			
Trtmt	Source	Rate	Timing[1]			
#		lb N / A	PP, P, E, PH	June 24	July 7	July 21
1	control	30	0, 30, 0, 0	8159	1478	510
2	urea	120	0, 30, 50, 40	14060	7638	3041
3	urea	180	0, 30, 70, 80	18391	11933	8276
4	urea	240	0, 30, 90, 120	19571	16143	11657
5	urea	240	0, 30, 50, 160	18280	13742	12021
6	urea	300	0, 30, 90, 180	20757	17278	13350
7	ESN	180	150, 30, 0, 0	19686	10393	5949
8	ESN	240	210, 30, 0, 0	21088	16371	11241
9	ESN	180	0, 30, 150, 0	17963	13680	6568
10	ESN	240	0, 30, 210, 0	19555	17101	11687
			Significance[2]	**	**	**
			LSD (0.10)	1821	2119	2229

[1]PP, P, E, PH = Preplant, Planting, Emergence, and Post-Hilling, respectively;
4 post-hilling applications were as follows: 20%, 20%, 30%, 30%.
[2]NS = Non-significant; ++, *, ** = Significant at 10%, 5%, and 1%, respectively.

Table 12. Effect of N rate, source, and timing on Premier Russet petiole nitrate-N levels.

Nitrogen Treatments				NO_3-N, ppm		
	N	N	N			
Trtmt	Source	Rate	Timing[1]			
#		lb N / A	PP, P, E, PH	June 24	July 7	July 21
1	control	30	0, 30, 0, 0	8373	678	320
2	urea	120	0, 30, 50, 40	16267	6640	3052
3	urea	180	0, 30, 70, 80	18834	10370	8233
4	urea	240	0, 30, 90, 120	20492	13747	11409
5	urea	240	0, 30, 50, 160	17723	12400	9589
6	urea	300	0, 30, 90, 180	22119	16050	13994
7	ESN	180	150, 30, 0, 0	16844	6878	3202
8	ESN	240	210, 30, 0, 0	20657	14091	8513
9	ESN	180	0, 30, 150, 0	17628	12305	5363
10	ESN	240	0, 30, 210, 0	19098	15100	10236
			Significance[2]	**	**	**
			LSD (0.10)	2371	2102	1771

[1]PP, P, E, PH = Preplant, Planting, Emergence, and Post-Hilling, respectively;
4 post-hilling applications were as follows: 20%, 20%, 30%, 30%.
[2]NS = Non-significant; ++, *, ** = Significant at 10%, 5%, and 1%, respectively.

Table 13. Effect of N rate, source, and timing on Bannock Russet petiole nitrate-N levels.

Nitrogen Treatments				NO_3-N, ppm		
	N	N	N			
Trtmt	Source	Rate	Timing[1]			
#		lb N / A	PP, P, E, PH	June 24	July 7	July 21
1	control	30	0, 30, 0, 0	7773	3189	377
2	urea	120	0, 30, 50, 40	14305	6546	4212
3	urea	180	0, 30, 70, 80	18794	9227	8985
4	urea	240	0, 30, 90, 120	20850	14480	11714
5	urea	240	0, 30, 50, 160	18004	11397	12935
6	urea	300	0, 30, 90, 180	21177	15971	13994
7	ESN	180	150, 30, 0, 0	16803	7823	4283
8	ESN	240	210, 30, 0, 0	21220	14419	9673
9	ESN	180	0, 30, 150, 0	19017	12001	7474
10	ESN	240	0, 30, 210, 0	19289	15074	10491
			Significance[2]	**	**	**
			LSD (0.10)	1397	2463	1577

[1]PP, P, E, PH = Preplant, Planting, Emergence, and Post-Hilling, respectively;
4 post-hilling applications were as follows: 20%, 20%, 30%, 30%.
[2]NS = Non-significant; ++, *, ** = Significant at 10%, 5%, and 1%, respectively.